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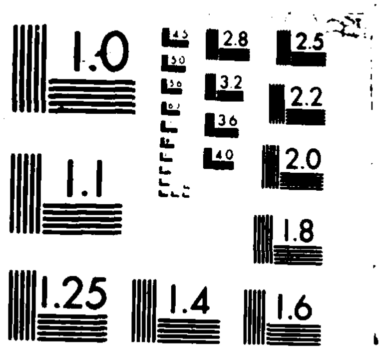


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# EVALUATION AND ANALYSIS OF GAS TURBINE INTERNAL FLOW RESTRICTORS

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August 1986

Final Report for period August 1985 - April 1986



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A comprehensive review of the literature concerning pressure loss calculations for flow through turns and bends, dividing and combining branches, sudden area changes, and orifices was conducted. An evaluation of the proposed analytical procedures was made on the bases of applicability to gas turbine internal flow systems, accuracy of the flow characteristic predictions, and the complexity of the restriction modeling. A standardized loss analysis procedure for each restriction type was selected from the reliable pressure loss models available in the literature. Keywords


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# FOREWORD

This informal technical report describes technical work accomplished during the Evaluation and Analysis of Gas Turbine Internal Flow Restrictors program conducted under Contract F33615-85-C-2575. The work described was performed during the period 1 August 1985 to 20 April 1986. This contract with Universal Energy Systems, Inc. and Allison Gas Turgine Division of General Motors Corporation was sponsored by the Aeropropulsion Laboratory, United States Air Force, Wright Patterson AFB, Ohio, with Mr. Richard Martin (AFWAL/POTX) as Project Engineer. Technical coordination was provided by 2nd Lt. Gary Willmes. Contract was managed by Dr. James R. Twist.

The technical effort reported was directed by Dr. Philip Snyder and supervised by Mr. Rodney Vogel. Mr. W. David McNulty collected much of the reference material for the research.

Publication of this report does not constitute Air Force approval of the findings or conclusions presented. It is published only for the exchange and stimulation of ideas.

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# I. INTRODUCTION

The performance of a modern, high temperature gas turbine engine is compromised significantly by associated requirements for component cooling This cooling is normally accomplished with air bled from the "cold", compressor end of the engine. Consequently, the paths provided to conduct this cooling air require careful design and flow analyses for effective utilization of bleed air resources. Gas path leakage, which may not provide any useful function, occurs between engine components. The combined cooling and leakage flows must be determined and their impact on engine performance evaluated.

The determination of these cooling and leakage flows, called the internal flow analysis, requires the mathematical modeling of a complex network of conduits and restrictions located inside and outside the main gas path from the engine inlet to the final nozzle. The total pressure losses through these conduits and restrictions must be characterized so that the flow capacities can be calculated. Two parameters are used somewhat interchangeably for the flow characteristics or the total pressure loss characteristics of the constituent restrictions. The discharge coefficient, $C_D$, is a measure of the flow passing through a restriction relative to the calculated ideal flow at the actual upstream and downstream pressures. The total pressure loss coefficient, k, is a measure of the energy required to drive the actual flow through the restriction. For example at the same operating conditions, the discharge coefficient and the total pressure loss coefficient based on maximum upstream dynamic pressure are related as

$$C_D = \frac{1}{\sqrt{k - k_e + 1}}$$

for a restriction in the incompressible flow regime.[1]

[1]Nomenclature definition is found on page 122.

The purpose of this program is to formulate flow characteristic models for conduit bends and turns, branches, sudden area changes, and orifices applicable to the restrictions in the internal flow systems of gas turbine engines.

Modeling of flow through the interior cooling and leakage passages of gas turbine engines is an inexact science. These passages are often of unconventional geometries for which experimental data do not exist and for which numerical fluid dynamic analysis is unreliable or impractical. As the result of in situ performance variations due to local conditions of turbulence, approaching flow profile characteristics, proximity of downstream restrictions, heat transfer, and engine-to-engine configuration and dimensional variations, careful rig tests on the actual engine parts will not yield precise flow characteristics for the internal flow system model. These uncontrollable consequences of gas turbine engine design distinguish this flow network analysis from the more exact solutions for conventional piping or ducting systems. The accurate modeling of internal flow systems of gas turbine engines now relies on the modification of "reference" restriction characteristics with application-specific empirical factors based on global experience from engine testing. These limitations do not preclude the reasonable preliminary predictions of internal flow system performance for untested engine designs. Fortunately, the internal flow system is typically comprised of many restrictions in series and parallel arrangements. The composite nature of such flow networks generally relegates the flow restriction characteristics to secondary importance with respect to the correct evaluation of flow areas.

An exhaustive literature search indicated that the k-factor is the parameter of choice for general restriction geometries. However, the definition of the k-factor does not enjoy the same consensus. The flow models presented in this report are based upon total pressure loss k-factors which are referenced to flow conditions calculated at the minimum cross-sectional area at the upstream end of the restriction. The rationale for this selection is discussed in the theoretical analysis section.

The important objectives of k-factor modeling are:

1) Prediction of realistic trends and boundary values[2] at approximately correct levels of k-factor for the component geometry at local average flow conditions.

2) Relatively simple (usable) formulation of the primary geometric and fluid dynamic parameters into a correlation representative of a broad range of configurations and flow environments.

Such k-factor models allow realistic comparisons for the evaluation of design changes and environment modifications. Prediction of absolute performance levels will usually require an experienced adjustment of the appropriate k-factors to match experimental results.

Often internal flow system models for new engine designs are synthesized initially with k-factors for a static orifice, $k = 2.7$, and for an isentropic nozzle, $k = 1.0$, in conjunction with exact calculations of the controlling passage areas. These models can be surprisingly accurate when carefully formulated by an experienced flow analyst. The preliminary internal flow model is refined using component k-factors appropriate to the engine design details. Later, when engine performance testing yields measured pressures and temperatures for the internal cavities and passages, the k-factors for the controlling restrictions can be modified to simulate the in situ pressure changes.

Assessing the validity and accuracy of k-factor models for even basic restriction geometries is difficult or impossible without extensive experimental support. Generalized k-factor models are nonexistent for the

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2 These "boundary values" could also be termed limiting or extremum values. As an example, the flow losses for bends of increasing radius ratio, $r/a$, or decreasing bend angle, $\theta$, should approach the wall friction loss for a straight duct of equal bend length and the same cross-sectional geometry as a lower limit.

broader range of restriction geometries necessary for gas turbine internal flow analysis. When the effects of unconventional installations and fluid flow environments are considered, the ability to precisely predict restriction flow characteristics is presently unattainable. However, the purpose of this study is to develop approximate k-factor models for generic bends and turns, branches, sudden area changes, and orifices common to gas turbine secondary flowpaths. These algorithms will produce representative trends and boundary values for the identifiable variables of the geometry and the flow processes.

Open literature contains many performance models for the basic restrictions. Some of these empirical models were derived from poorly controlled or incompletely formulated experiments. Consequently, some of the available k-factor models are limited to unspecified ranges of influential geometric and/or flow parameters. A few k-factor models even produce physically inconsistent performance predictions in particular operating regimes. A small sample of these exceeding limited k-factor predictions are derived from oversimplified analytical models of the flow phenomena.

Sometimes recognized expert opinions exist about the reliability of certain restriction models. Beyond this the only viable procedure for selecting among the potpourri of k-factor models must rely upon comparisons of performance predictions at selected conditions for several of the more comprehensive models and upon evaluation of their boundary values where possible. The development of the k-factor models, or perhaps more correctly the synthesis of the k-factor models, for application to the analysis of internal flow systems in gas turbine engines will be accomplished with such a procedure. One or more sources will be utilized to produce a consistent algorithm of acceptable accuracy that will predict realistic performance trends for variations in component geometry and flow conditions.

The k-factor models sought in this study will be formulated with influence coefficients to correct the "reference" performance predicted for a basic geometry and flow environment, e.g.,

$$k^* = f(x, y, z, Re)$$

for the effects of non-standard geometry or unusual flow conditions,

$$k = C_i \; C_f \; C_M \; k^{*}$$

Basic flow environments are generally for the isolated component in the incompressible regime. This implies fully developed entrance flow and the effect of complete downstream pressure recovery. The influence coefficients for variations from the basic geometry or standard incompressible flow characteristics will be developed from available data sources. It is worth noting that the k-factors referenced to the dynamic pressure remain relatively constant for many restriction components over a wide range of flow conditions. Therefore, when information does not exist to permit the extension of a model to a broad spectrum of operating environments, the application of the incompressible characteristics to high velocity flows still may be warranted.

# II. THEORETICAL ANALYSIS

The analyses of the internal flow systems of gas turbine engines are based on traditional one-dimensional compressible formulas where the parameter gradients and the velocity profiles are approximated by "average" conditions,

$$\bar{V} = \dot{m} / \bar{\rho} \ A .$$

Then the apparent loss of "average" total pressure, which results from the use of effective velocity to represent velocity profile, is absorbed in the real system total pressure loss (1).[3] The internal flow system is "complex" from the standpoint that most of its duct geometry changes (form drag) tend to overwhelm wall friction (skin drag) as the source of total pressure losses. The proximity of the restrictions in series is such that fully developed laminar or turbulent flow is seldom achieved. This transitional flow environment contributes to the uncertainty of the one-dimensional analysis. However, the basic simplicity of the formulation and the ability to iterate the model coefficients from experience make the approach viable and perhaps preferable.

The calculation for internal flow system performance generates a network of flows, pressures, and temperatures throughout the cooling and leakage paths in the engine. The steady-state solution has an electrical analog where the restriction k-factors are similar to the resistances and the flows (currents) are found by Kirchoff's law. The total pressures are comparable to the node voltages. The most important descriptors for a typical internal flow system model are the accurate values for flow path cross-sectional areas. The flow area is crucial to the determination of flow and is of first order importance in the estimation of the total pressure loss across restrictions. The basis for defining the k-factor models and the application of these models to the duct geometries which are encountered in gas turbine internal flow systems are discussed.

3 Bracketed numbers refer to References, page 69.

## Selection of the Generalizing Parameter for k-Factor

Conventional usage employs the dynamic pressure,

$$q = \rho V^2 / 2 ,$$

as the reference parameter for generalizing internal as well as external drag and pressure loss coefficients for incompressible flows. However, when compressibility effects become important to high velocity flows of gases, there seems to be no consensus on the reference parameter for drag and pressure loss calculations. External aerodynamics has retained the dynamic pressure reference on a uniform basis,

$$F_d = C_d \, (\rho_0 V_0^2/2) A_{ref}$$

Internal aerodynamics vacillates between the traditional dynamic pressure, $q$, and the impact pressure, $(P - p)$,

$$P_1 - P_2 = k \, q_{max} \qquad \text{or} \qquad P_1 - P_2 = k^+ \, (P - p)_{max}$$

Both parameters are functions of Mach number and $\gamma$,

$$\frac{q}{P} = \frac{\gamma}{2} M^2 \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{1 - \gamma}}$$

and

$$\frac{P - p}{P} = 1 - \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{1 - \gamma}}$$

Therefore, either is capable of serving as the generalizing parameter for the kinetic energy effects in compressible flow. In fact, the pressure loss coefficient based on reference area, $A_n$, for any restriction can be converted between a dynamic pressure basis and an impact pressure basis without loss of accuracy or generality as

$$k_n = \left[ \frac{\left( 1 + \frac{\gamma - 1}{2} M_n^2 \right)^{\frac{\gamma}{\gamma - 1}} - 1}{\frac{\gamma}{2} M_n^2} \right] k_n^+$$

For incompressible flow,

$$k_n = k_n^+$$

since

$$P - p = q \quad .$$

Some k-factor data are referred to restriction exit (downstream: n = 2) conditions. This k-factor definition requires an additional iteration to establish the total pressure loss across each restriction. For a given flowrate, total temperature, and duct area, a downstream total pressure must be assumed,

$$\frac{\dot{m}\sqrt{T}}{P_2 \; A_2} \rightarrow M_2 \rightarrow \left(\frac{q}{P}\right)_2$$

When

$$P_2 = P_1 - k_2 \; q_2 = P_{2 \text{ assumed}}$$

the solution has been found. This complication is avoided by using a direct serial solution involving the maximum dynamic pressure at the restriction entrance (upstream: n = 1) as the reference parameter. The upstream and downstream k-factors for a specific restriction are related implicitly by

$$k_1 = \frac{\left(\frac{q}{P}\right)_2}{\left(\frac{q}{P}\right)_1} \left[ \frac{k_2}{1 + k_2 \left(\frac{q}{P}\right)_2} \right]$$

A certain commonality is exemplified by the conventional use of dynamic pressure as the reference parameter for the surface drag coefficient for the compressible flow over immersed bodies and for the wall friction in conduits (FANNO flow).

Benedict and Carlucci (2) have shown that the application of k-factor values based on inlet conditions, $k_1$, to the equivalent length analysis where

$$4 \; f \frac{\ell}{HD} = k_1 \quad ,$$

will overestimate the total pressure loss for compressible flow. The k-factor or 4 f $\ell$/ D in this FANNO type analysis is applied to a continually increasing dynamic pressure due to a uniformly distributed loss mechanism through the "constant area" restriction. Therefore, a smaller k-factor correlates with the total pressure loss at a given inlet flow condition.

Very little reliable data are available on the k-factors for restrictions of conventional geometry operating in the compressible flow regime. Almost no data exist for the more unusual restriction configurations common to gas turbine internal flow systems. The best data are normally found for incompressible flow through typical pipe and duct geometries. Fortunately, the k-factors based on maximum inlet dynamic pressure are relatively insensitive to Mach number for many restrictions (3). The compressibility effects generally become important above Mach 0.3 where the velocities approach or exceed the critical Reynolds number so that the flow is in the fully turbulent regime.

The selection of maximum inlet dynamic pressure as the reference parameter for total pressure loss coefficients has the merit of minimizing coefficient sensitivity to compressibility effects for most loss mechanisms. The dynamic pressure is analogous to the kinetic energy of the fluid stream. The impact pressure includes the latent energy absorbed by the compressibility of the fluid in addition to the kinetic energy. The maximum inlet dynamic pressure was chosen as the reference parameter for generalizing the characteristics of the total pressure loss coefficients for all of the restriction geometries investigated, with the exception of the sudden expansion. The use of the maximum inlet impact pressure to characterize the sudden expansion results in the advantage of a unity loss coefficient for any jet discharging into a large plenum. The selection of dynamic pressure or impact pressure as the generalizing parameter, and the choice of reference area at the inlet or exit of the restriction is arbitrary. However, the k-factor must be applied to the value of the generalizing parameter for which it was derived at the restriction area to which it was referenced to produce correct predictions of total pressure loss.

## Solutions with Duct Cross-sections of Untested Configuration

Most pressure loss data available in the public domain are for circular or rectangular duct cross-sections. Some data exist for annular duct geometries, but their restriction configurations are limited primarily to constant area and gradual expansions. However, many unusual duct shapes, and particularly annular ducts, are encountered in the analysis of the internal flow systems of gas turbine engines. Consequently, when the diameter of an equivalent circular cross-section is required for the evaluation of a flow parameter such as Reynolds number or equivalent duct length, the hydraulic diameter is generally employed,

$$HD = \frac{4\ A}{P}$$

For a circular duct $\quad HD = d \quad$ so that

$$A = \frac{\pi}{4} HD^2$$

For an elliptical duct $\quad HD \simeq \dfrac{2\ a\ b}{\sqrt{2\ (\ a^2 + b^2\ )}} \quad$ so that

$$A \simeq \frac{\pi}{4} HD \sqrt{\frac{a^2 + b^2}{2}}$$

For an annular duct $\quad HD = D - d \quad$ so that

$$A = \pi \left( \frac{D + d}{2} \right) \frac{HD}{2}$$

For a rectangular duct $\quad HD = \dfrac{2\ a\ b}{(\ a + b\ )} \quad$ so that

$$A = (\ a + b\ ) \frac{HD}{2}$$

An analogy between annular and rectangular cross-sections reveals that as $a/b \rightarrow 0$, the rectangle becomes similar in geometrical characteristics to an annulus of small hydraulic diameter where

$$\pi \left( \frac{D + d}{2} \right) \rightarrow (\ a + b\ )$$

and

$$\lim_{a/b \to 0} HD = \frac{2\ a}{\frac{a}{b} + 1} = 2\ a$$

or more simply

$$\pi\ D = b$$

and $\frac{1}{2}\ (\ D - d\ ) = a$

This artifice permits the evaluation of many annular restrictions from the comparable restriction data for the analogous rectangular duct.

The applications of the theoretical analyses selected for deriving pressure loss algorithms for turns and bends, combining and dividing branches, sudden expansions and contractions of flow area, and orifices will be discussed in the following sections.

## III. TOTAL PRESSURE LOSS COEFFICIENTS FOR TURNS AND BENDS

Bends are among the more difficult internal flow loss geometries to estimate accurately. The duct geometry and condition of the flow exert very strong influences on the total pressure loss due to the generation of complex secondary flows and downstream recovery processes. For example, circular-arc bends of round or square cross-section develop twin counter-rotating helical vortices which tend to stabilize the flow, as shown in Figure 1. If the duct cross-section is unconventional, e.g., triangular, polygonal, etc., the secondary flow can become complicated with more than two vortices. Inversely, turning in a duct with a narrow annular cross-section may not produce any secondary flow. Combining the effects of duct shape and wall roughness with the rate and amount of turning makes the loss analysis for simple, single circular-arc bends very difficult.

The location and flow environment of bends in turbine engine cooling and leakage paths rarely meet the modeling criteria for upstream and downstream tangent lengths or fully developed velocity profiles. The total pressure loss in a bend is very sensitive to the conditions in the entering flow as established by upstream tangent length, wall roughness, and flow disturbances. The length of the downstream tangent and flow blockage is even more important to the pressure loss as the result of the nature of the recovery process in the flow leaving the bend. Bends in gas turbine engine flow systems are routinely in the region of influence of upstream and downstream restrictions, which contributes to the difficulty of predicting total pressure losses. In addition, the flow area through the bends frequently changes in cooling and leakage paths. The consideration of these application variables make the total pressure loss prediction for internal flow system bends uncertain at best.

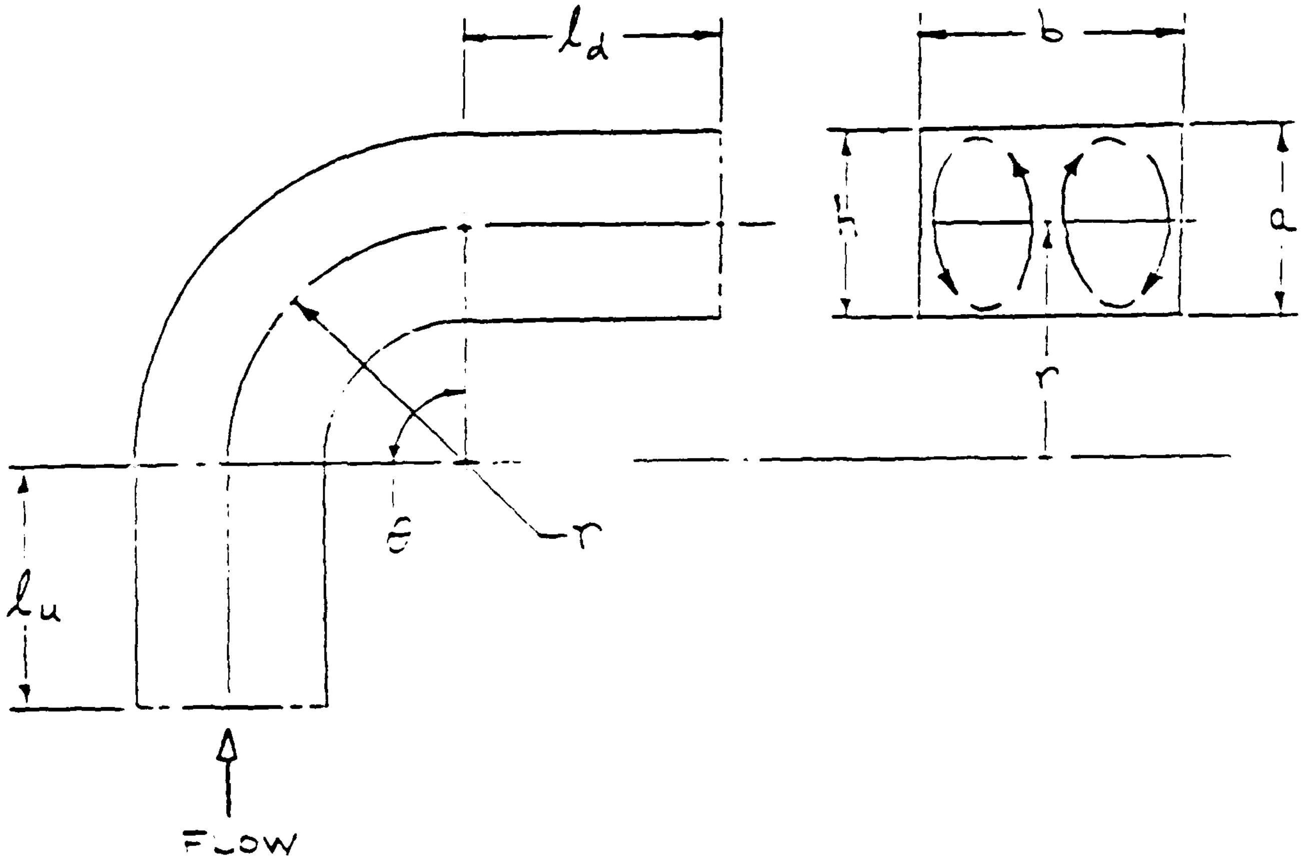



FIGURE 1 GENERAL CONFIGURATION OF CIRCULAR-ARC BENDS

Bends can be classified according to distinct physical characteristics of the flow. The rate of turning has the greatest effect on the flow through bends and is used in Table I to distinguish among the primary types and the physical processes dominating their particular flow fields.

Table I.
Classification of Simple Circular-Arc Bends on the Basis of the Loss Mechanisms Dominating the Flow Fields.

| Bend Type | r/h | Predominant Loss Mechanism |
|---|---|---|
| Long Bends | > 14 | Wall friction |
| Short Bends | < 14<br>> 0.5 | Combined flow separation and wall friction |
| Mitre Bends | < 0.5 | Flow separation |

Reference to Figure 2 shows that turning flow in most gas turbine engine restrictions resides in the short bend (and mitre bend) category. As the result of the generally elevated pressures and temperatures and the high flow velocities in gas turbine engines, the flow in short bends will usually be turbulent, $R_e > 20000$, as predicted by Figure 3.

The analysis of internal flow systems in gas turbine engines must attempt to account for the effects of the many variables which influence the total pressure loss in a bend. The effects of the following parameters on bend losses are usually considered where the availability of quantitative data permit:

Bend Geometry
- cross-sectional shape
- turning rate
- amount of turning
- area change

Bend Flow Conditions
- laminar, transitional, or turbulent
- wall roughness
- upstream tangent length
- downstream tangent length

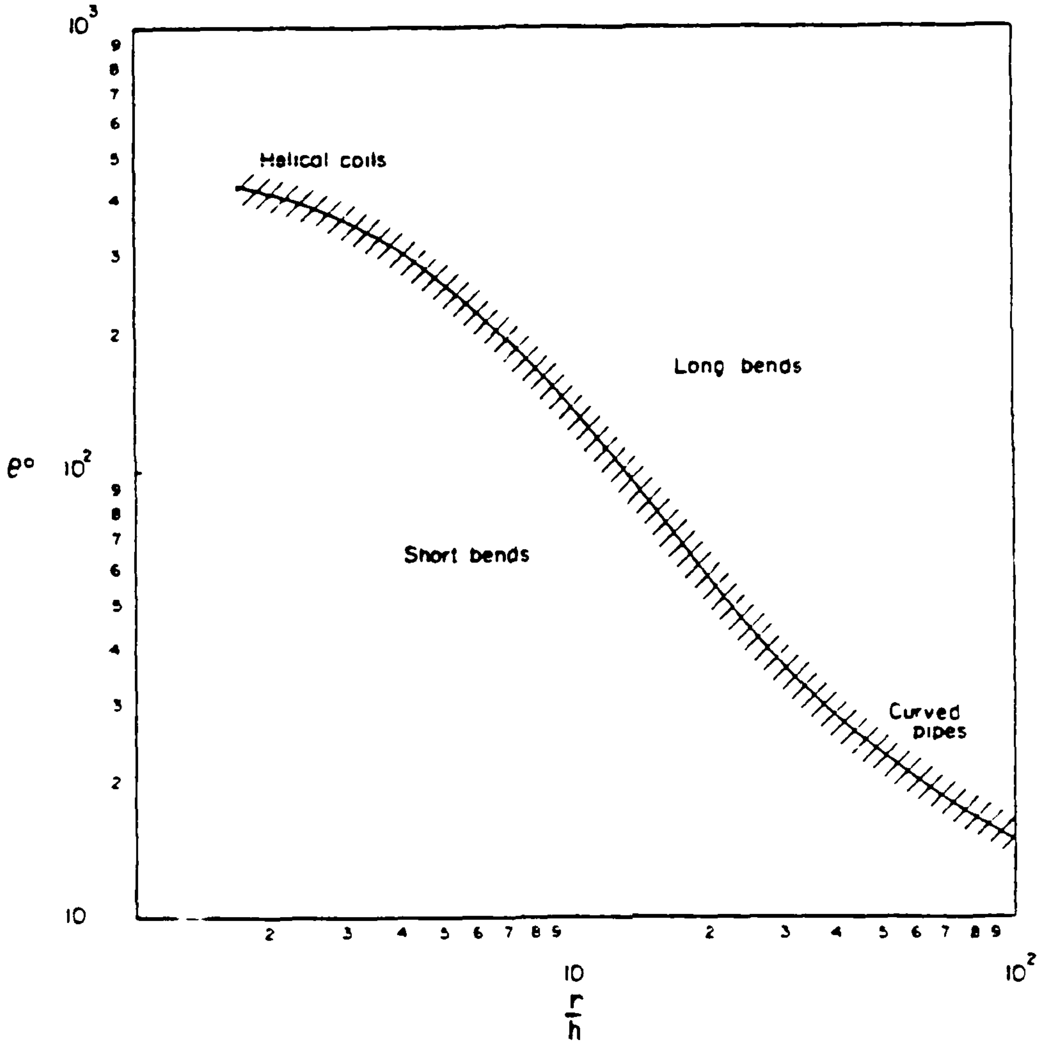



FIGURE 2. BOUNDARY BETWEEN LONG AND SHORT CIRCULAR-ARC BENDS. Reference (4)

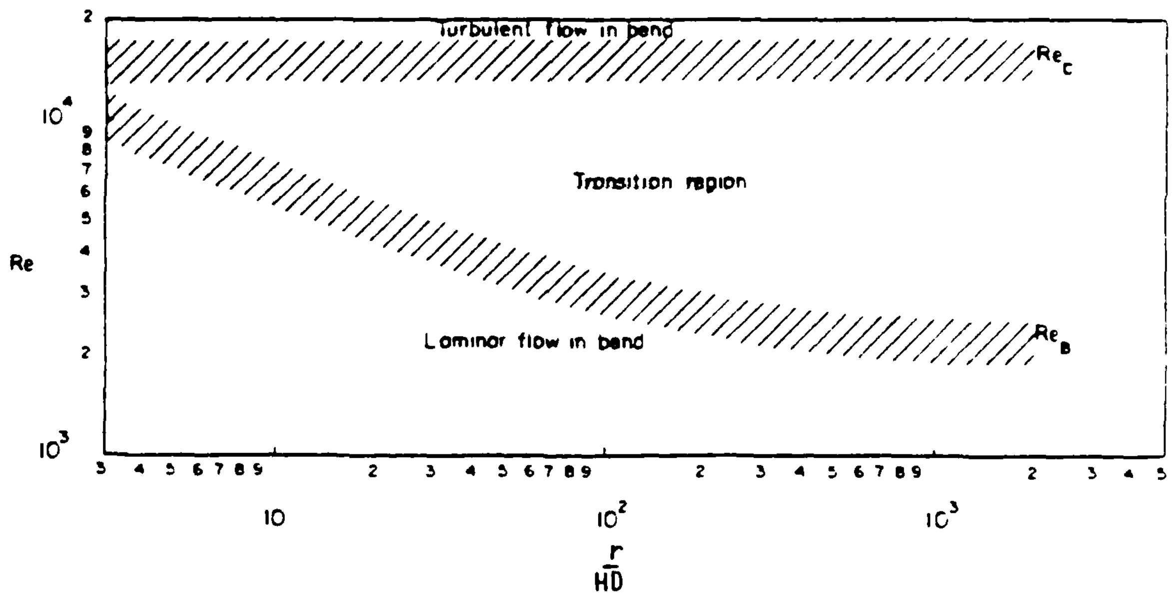



FIGURE 3. TRANSITION REGION FOR FLOW IN LONG CIRCULAR-ARC BENDS. Reference (4)

The evaluation of these effects will be discussed as they apply to the single circular-arc bend types. The modeling of compound bends and multiple bends will not be considered. The bibliography contains several references which treat these subjects in varying degrees of analytical depth. Miller (5) and ESDU (6) are recommended sources of reliable performance data. The algorithms presented for bend losses apply to turbulent, incompressible flow. The reliable data references seem to agree upon the application of the incompressible loss factors to compressible flows within the present state-of-the-art. The experimental and analytical data are not yet sufficiently reliable to warrant a distinction at this time.

When a more precise solution is required, and the bend installation and flow quality justify the analytical complexity, reference (4) can be used to model bend K-factors.

Basic Circular-Arc Bends

The empirical model for K-factors proposed by Ito (7) is recommended for turbulent flow through bends of circular cross-section in references (1), (4), and (8), among others. The total pressure loss predicted by the Ito model is slightly greater than that predicted in reference (9). However, the wall friction loss is included in the Ito formulas while the plots in reference (9) represent turning loss alone,

$$K_{b(9)} \simeq K_{b(7)} - 4f\ \theta\left(\frac{r}{HD}\right)_b$$

The bend model by Ito is limited to hydraulically smooth walls so that a correction for rough walls is required. Although the algorithm has been validated by test data for a Reynolds number range of $2\ (10^4)$ to $4\ (10^5)$, the formulas can be extrapolated to a Reynolds number of $1\ (10^6)$ with acceptable accuracy. Bend loss does not change significantly with Reynolds number greater than $1\ (10^6)$.

Long Bends $Re\left(\frac{h}{r}\right)^2 < 364$

$$K_b = 0.01746\ \alpha\ f_c\ \theta\left(\frac{r}{h}\right)$$

Since this equation applies to a minimum r/h of 7.4, its use in gas turbine internal flow analysis arises infrequently.

The secondary flows present in bends of circular cross-section generate additional losses due to wall friction. These smooth-wall friction losses are correlated for curved turbulent flow at $Re\left(\frac{h}{r}\right)^2 < 1200$ by H. Ito (10) as

$$f_c = \frac{0.0205}{\left(\frac{r}{h}\right)^{1/2}} + \frac{0.304}{\left(R_e\right)^{1/4}}$$

The implied region of validity extends to short bends with r/h as small as 4.1 in addition to the entire long bend envelope.

Short Bends (not including mitre bends)

$$K_b = 0.00431\ \alpha\ \theta\ Re^{-0.17}\left(\frac{r}{h}\right)^{0.84}$$

The turning losses for long and short bends are correlated by the α term as determined from Table II.

A linear interpolation between the defined bend angles produces consistently smooth k-factor characteristics, as illustrated in Figure 4. The bend loss characteristics generated for 90 deg short bends are plotted in Figure 5.

Idel'chik contends in reference (13) that all turns and bends are essentially independent of the relative roughness, ε/ D, of the wall at Reynolds numbers

Table II.
Turning Loss Factors for the Bend Loss
Model by Ito (7).

| $\theta$-deg | r/h | $\alpha$ |
|---|---|---|
| 45 | | $\alpha = 1 + 5.13\left(\frac{r}{h}\right)^{-1.47}$ |
| 90 | < 9.85 | $\alpha = 0.95 + 4.42\left(\frac{r}{h}\right)^{-1.96}$ |
| | > 9.85 | $\alpha = 1.0$ |
| 180 | | $\alpha = 1 + 5.06\left(\frac{r}{h}\right)^{-4.52}$ |
| Proposed for interpolation, | | |
| 0 | | $\alpha = 1 + 6\left(\frac{r}{h}\right)^{-1}$ |

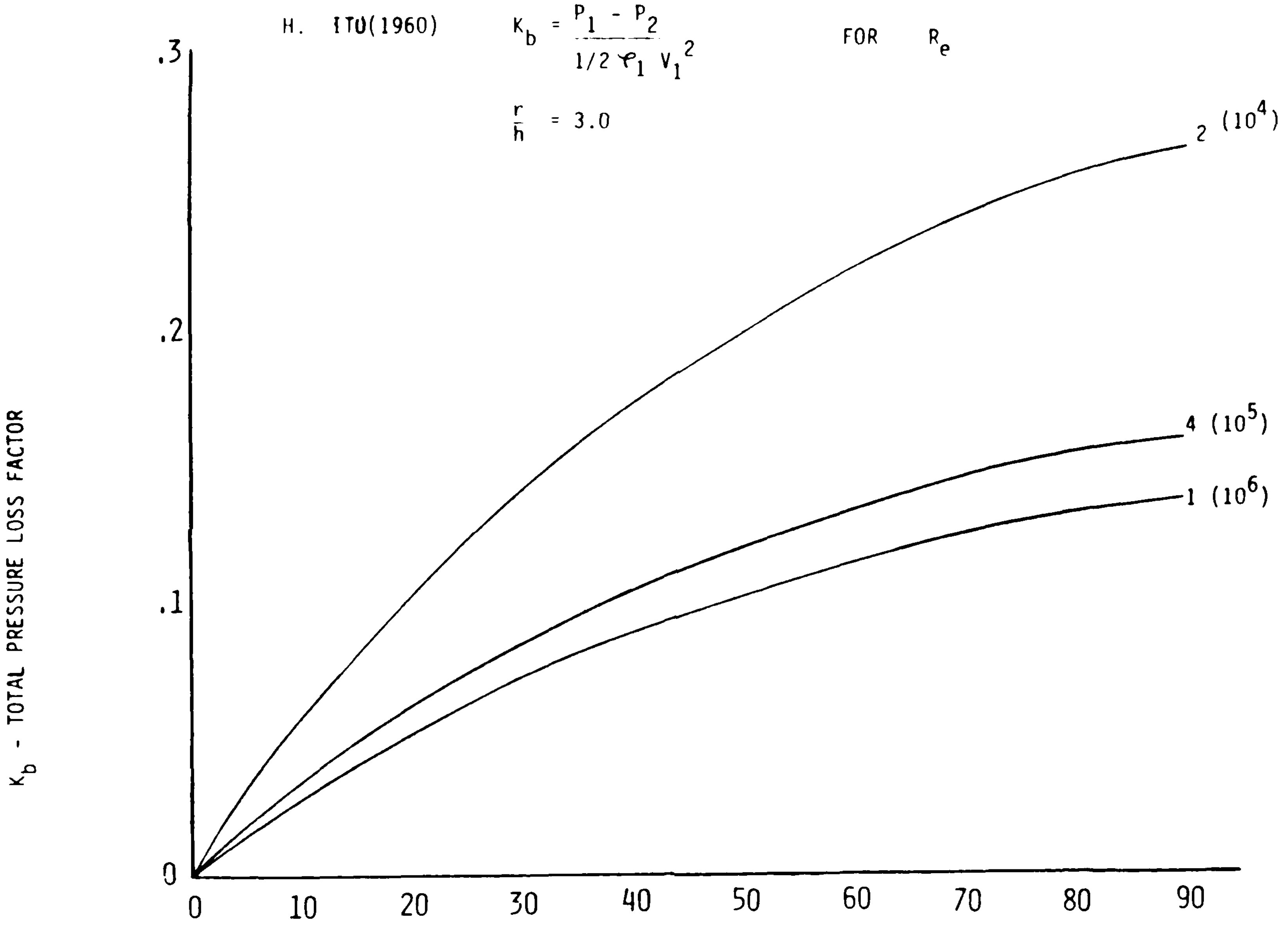



FIGURE 4 EFFECT OF BEND ANGLE ON THE TOTAL PRESSURE LOSS IN SHORT CIRCULAR-ARC BENDS

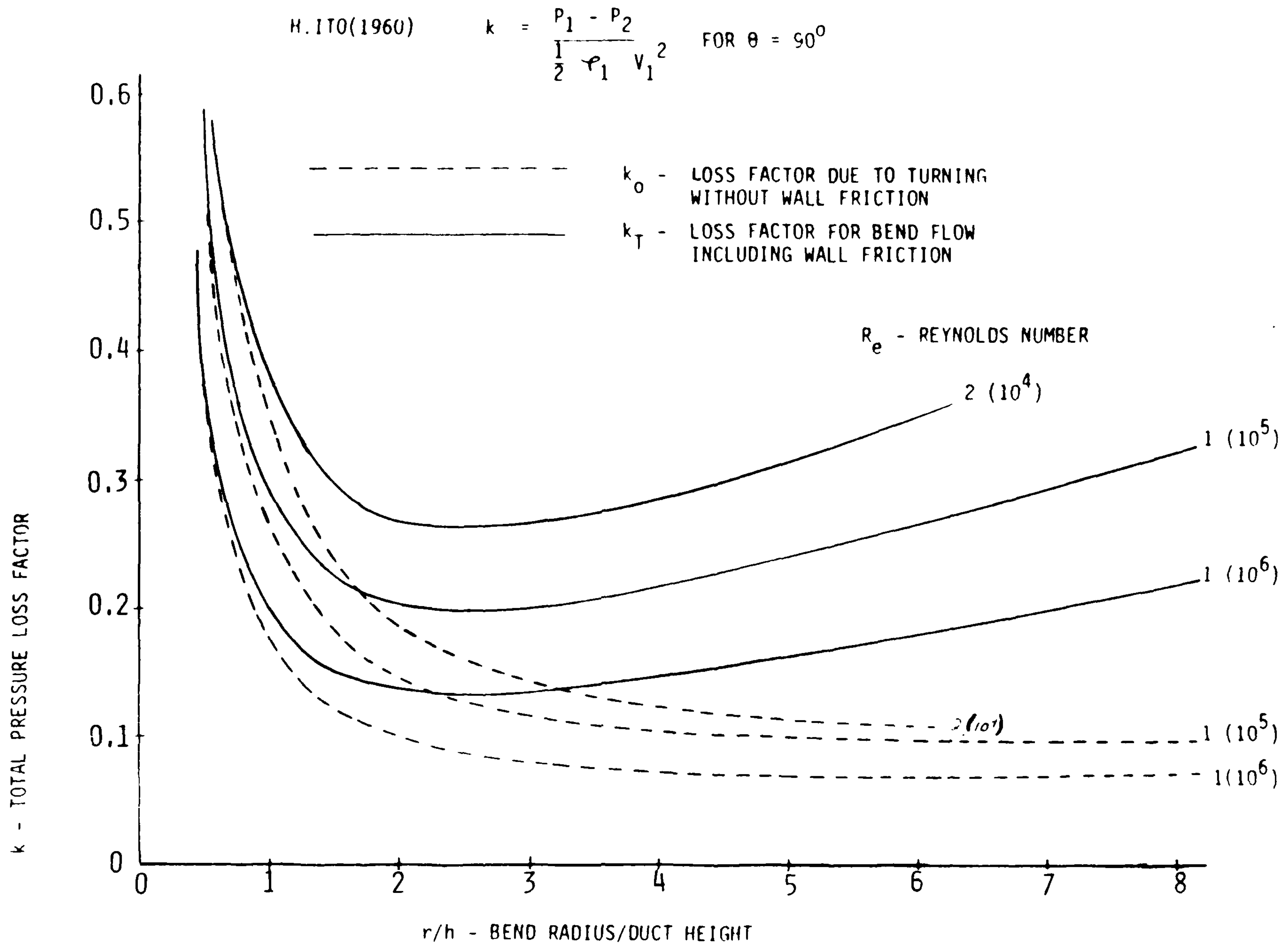



FIGURE 5 SINGLE SHORT CIRCULAR-ARC BENDS OF
$\theta$ = 90 DEG.

less than 4 ($10^4$). The formulation for the k-factor of long bends suggests a direct ratio of friction factors for a wall roughness correction as

$$C_f = \frac{f_{c\ rough}}{f_{c\ smooth}}$$

Unfortunately, reliable data to evaluate or substantiate this hypothesis were not found for friction factors of curved flows. Miller (5) suggests such a wall roughness correction based on straight pipe friction factors applied to all circular-arc bends. Idel'chik (13) restricts this correction factor to circular-arc bends with r/HD < 1.5. Both Idel'chik (13) and Henry (14) propose a stronger influence of wall roughness at Reynolds numbers above 2 ($10^5$) and for short bends with r/HD > 1.5. However, a maximum effect of $C_f = 2.0$ is proposed by Idel'chik for any combination of wall roughness and Reynolds number. An approximate model combining this general concensus was synthesized for short circular-arc bends as shown in Table III.

Table III.
Effect of Wall Roughness on Short Circular-Arc Bends.

| | |
|---|---|
| $R_e < 4\ (10)^4$ | $C_f = 1.0$ |
| $4\ (10^4) < R_e < 2\ (10^5)$ | $C_{f\ max} = 2.0$ |
| r/HD < 1.5 | $C_f = \frac{f_{rough}}{f_{smooth}}$ |
| r/HD > 1.5 | $C_f = \left(\frac{f_{rough}}{f_{smooth}}\right)^{1.75}$ |
| $R_e > 2\ (10^5)$ | $C_{f\ max} = 2.0$ |
| | $C_f = \left(\frac{f_{rough}}{f_{smooth}}\right)^{1.75}$ |

## Mitre Bends

The circular-arc bend degenerates into a special case where the concentric inner bend radius goes to zero at $r/h = 0.5$. Geometrical interfaces, size limitations, or ease of fabrication produce many bend restrictions with corner points at the inside wall and outside wall, $r/h = 0$. These bends and certain variations of similar type are categorized as mitre bends. The unifying characteristic of the flow through mitre bends is the high rate of turning. The separation and turbulent mixing flow processes dominate the total pressure losses in mitre bends so that Reynolds number effects are small to quite low values. Some dispersion is noted from source to source, but an average of data from references (1), (4), (9), and (11), plotted in Figure 6, is a good representation of the group. For most internal flow systems found in gas turbine engines the curve of Figure 6 can be adequately reproduced by the equation proposed by Hager (12) for bend angles greater than 25 degrees,

$$K_b = 2\left(1 - \cos \frac{3\theta}{4}\right)$$

As a rule of thumb, between bend angles of 5 degrees and 25 degrees

$$K_b = K_{b(12)} + 0.02$$

can be used.

Figure 7 shows the evolution of the mitre bend and some of the variations which are encountered in practice. Experience with these modified mitre bends has shown that the radius on the inside wall is the most influential geometry factor for reducing the K-factor (total pressure loss).

Corrections applicable to Figure 6 for these geometric variations are provided in Figure 8.

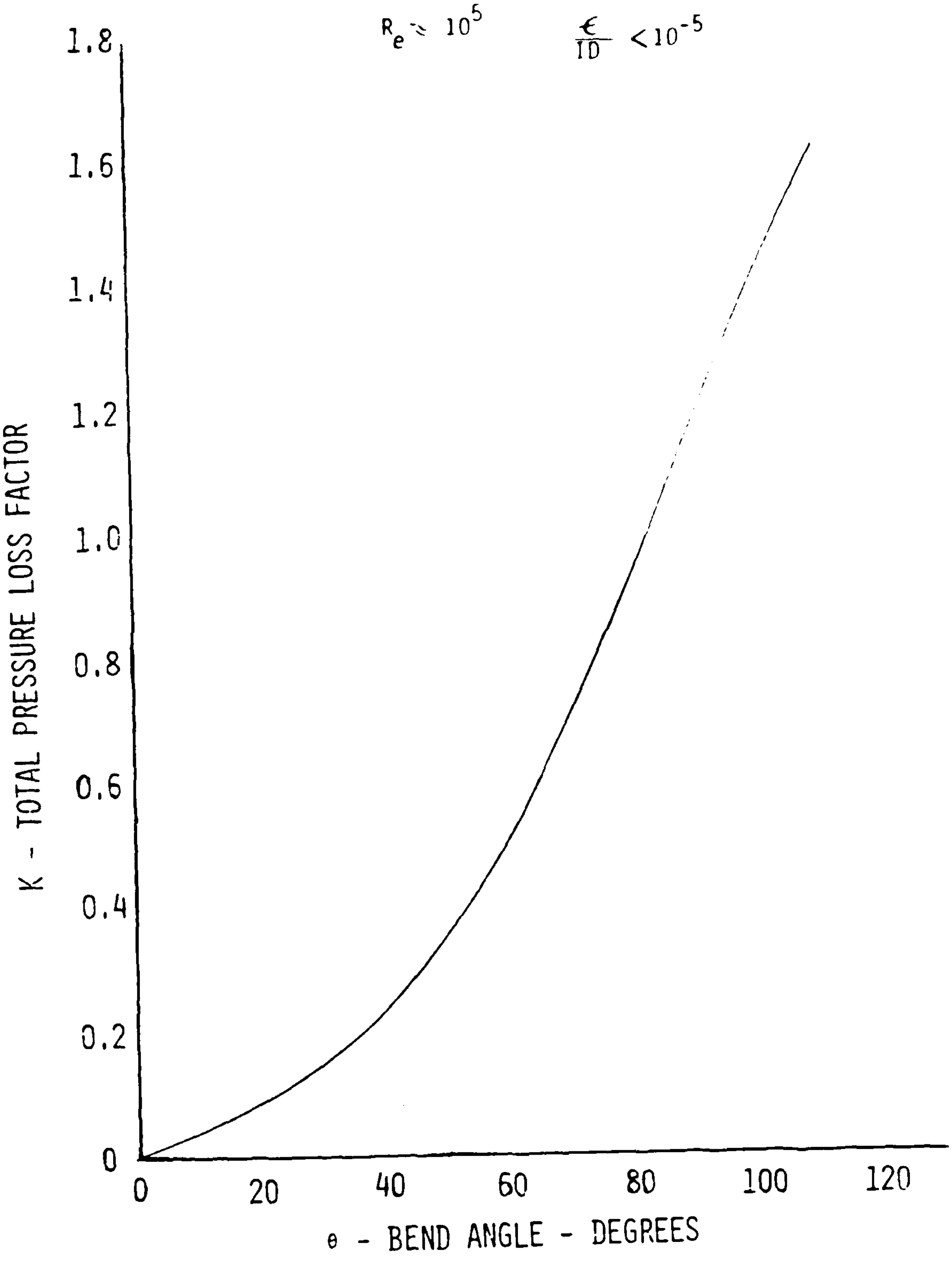



FIGURE 6 TOTAL PRESSURE LOSS FACTOR FOR A SINGLE MITRE BEND

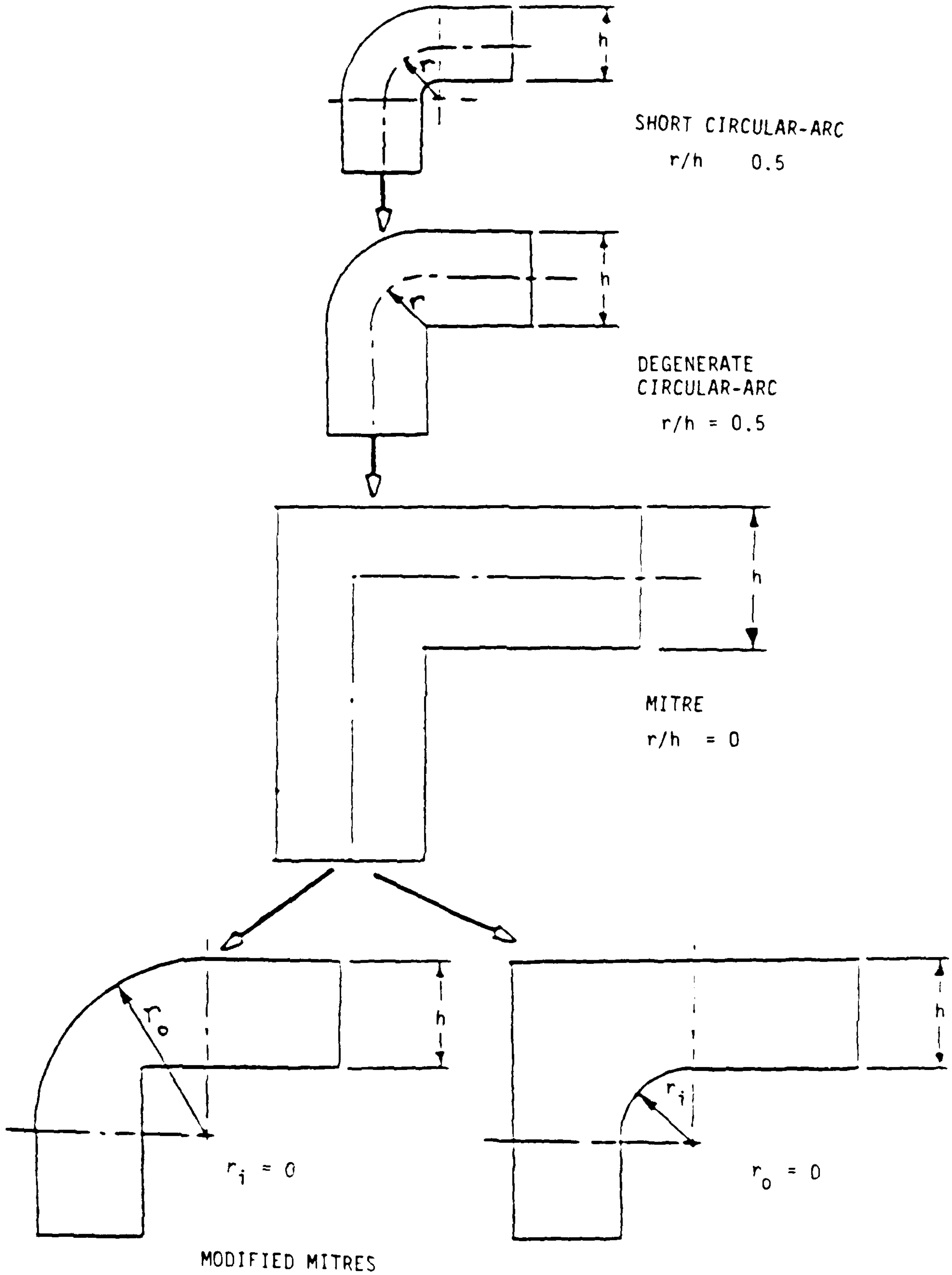



FIGURE 7 BEND MORPHOLOGY

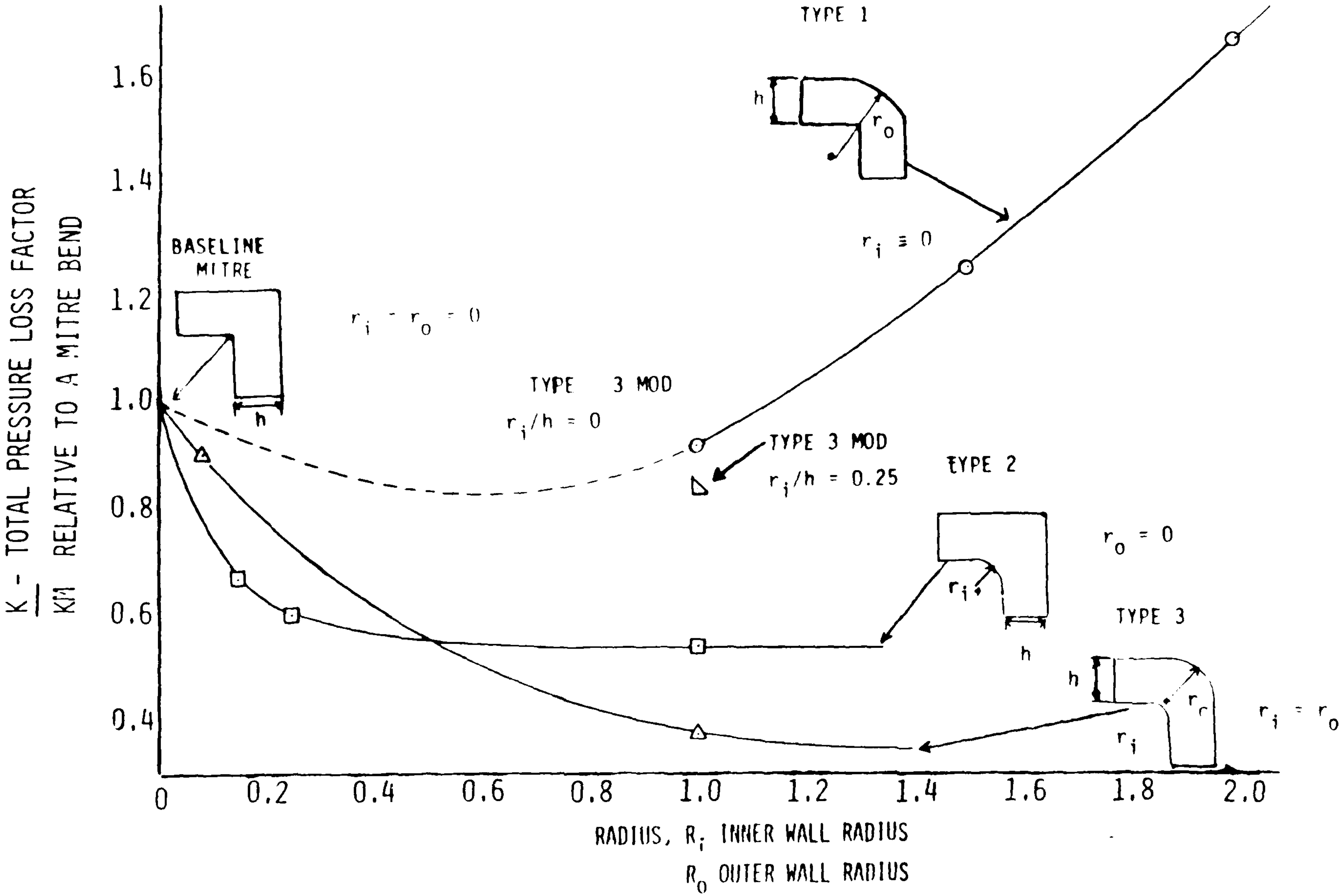



FIGURE 8 TOTAL PRESSURE LOSS CHARACTERISTICS FOR MODIFIED MITRE BENDS OF CONSTANT AREA WITH CONSTANT HEIGHT, , AT INLET AND EXIT

The data of references (4) and (13) indicate that very rough walls can increase the k-factor for mitre bends as much as 50% at Reynolds numbers above $4(10^4)$.

$$C_f \simeq 1 + 5\ (10^3)\left(\frac{\varepsilon}{HD}\right)$$

where $C_{f\ max} \simeq 1.5$

Below a Reynolds number of $4\ (10^4)$ the effect of roughness or Reynolds number on mitre bend k-factor is negligible.

Effects of Other Geometrical Parameters

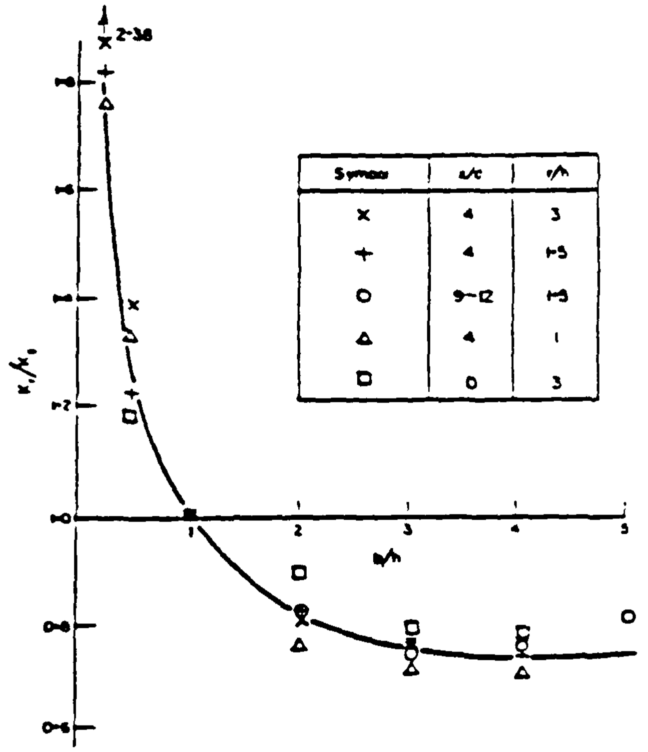
The basic bend model was derived for ducts of circular cross-section, but testing has shown that the algorithm represents flow through square ducts almost as well. From this point the bend model can be extended to include ducts of elliptical and rectangular cross-section. The bend model was formulated using the geometrical parameters D and h to accommodate this extended scope.

The pressure drop factors for the flow through bends of square and circular cross-section at the same values of r/h (including mitre bends), $\theta$, and $R_e$ are assumed to be negligibly different. Experimental correlations by Ward-Smith (15) and Miller (16) demonstrated this premise for $1\ (10^5) < R_e < 13\ (10^5)$. Figure 9 is a correlation of rectangular duct performance relative to circular ducts due to Ower and Pankhurst (17). The correction for rectangular bends can be represented by

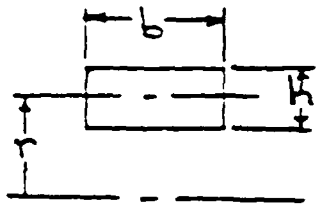
$$C_g = \frac{1}{2}\left(1 + \frac{b}{h}\right)\left(\frac{b}{h}\right)^{m-1}$$

$$\frac{k_r}{k_s} = \frac{1}{2}\left(1+\frac{b}{h}\right)\left(\frac{b}{h}\right)^{m-1}$$

| b/h | m |
|---|---|
| < 1 | 0.2551 |
| > 1 | 0.1386 |




Resistance of bends in pipes of rectangular cross-section.




$k_s$ - FACTOR FOR TOTAL PRESSURE LOSS IN A BEND OF SQUARE CROSS-SECTION, b = h.

$k_r$ = FACTOR FOR TOTAL PRESSURE LOSS IN A BEND OF RECTANGULAR CORSS-SECTION WITH ASOECT RATIO b/h.

FIGURE 9 RESISTANCE COEFFICIENT FOR BENDS OF RECTANGULAR CROSS-SECTION. REFERENCE (17)

where

| b/h | < 1 | > 1 |
|---|---|---|
| m | 0.2551 | 0.1386 |

The performance of elliptical ducts can be estimated from this correlation as a qualitative approximation. If more accurate analysis is required, reference (9) or (14) can be consulted for extensive data on bend performance of elliptical and rectangular ducts.

The basic bend model was derived from test data for fully developed turbulent flow at the inlet to the bend and for a least fifty diameters of downstream tangent length. The downstream tangent generally contributes mixing losses for lengths greater than two diameters. However, as the outlet tangent length diminishes toward zero, the k-factor increases as the initial pressure recovery process in the first two to four diameters of downstream tangent is lost. Miller (5) provides a convenient correction for downstream tangent length, shown in Figure 10. A $k^*_b = 1.2$ curve based on data in reference (4) has been added ostensibly for corrections to mitre bend k-factors. For ducts of particular rectangular cross-section Miller recommends the following modifications to $C_\ell$ of Figure 10:

if $b/h < 0.7$ and $\ell_d/HD > 1$,

$$C_{\ell r} = \frac{1 + C_\ell}{2}$$

If the bend or downstream tangent discharges into a larger duct or plenum, a sudden expansion loss must be added to $C_\ell$. Note that neither the bend k-factor nor $C_\ell$ include the wall friction loss $(4f\,\ell/D)_d$ associated with the downstream tangent length.

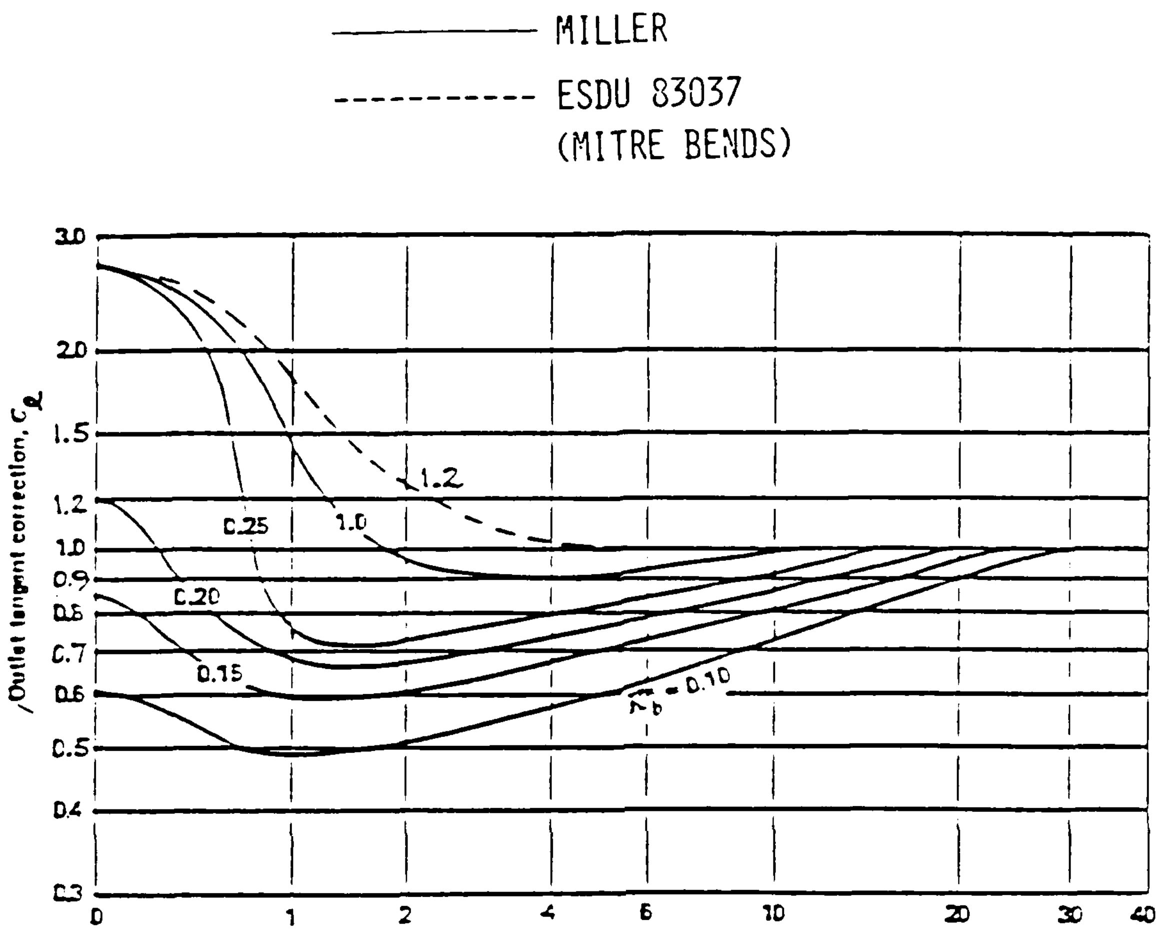



FIGURE 10 OUTLET TANGENT CORRECTION COEFFICIENT.
REFERENCES (5) AND (4)

The flow in gas turbine internal flow systems is often turned in annular ducts. These annular flow paths and conventional duct paths incorporate turning with area change in many restrictions. The effect of turning with area change in circular arc bends was correlated by Henry (14), Figure 11 Data for k-factors of mitre bends with area change were compiled by Idel'chik (13). A similar presentation of the data is provided in Figure 12. The severe effect of the sharp corner on the inside wall is evident from the inversion experienced by the loss coefficient, $C_A$. A sudden expansion alleviates some of the restriction at the mitre corner. The flow turns more gradually with less loss. A contraction at the separation point of the mitre corner restricts the downstream area available for turning. The flow contraction is amplified and the k-factor increases.

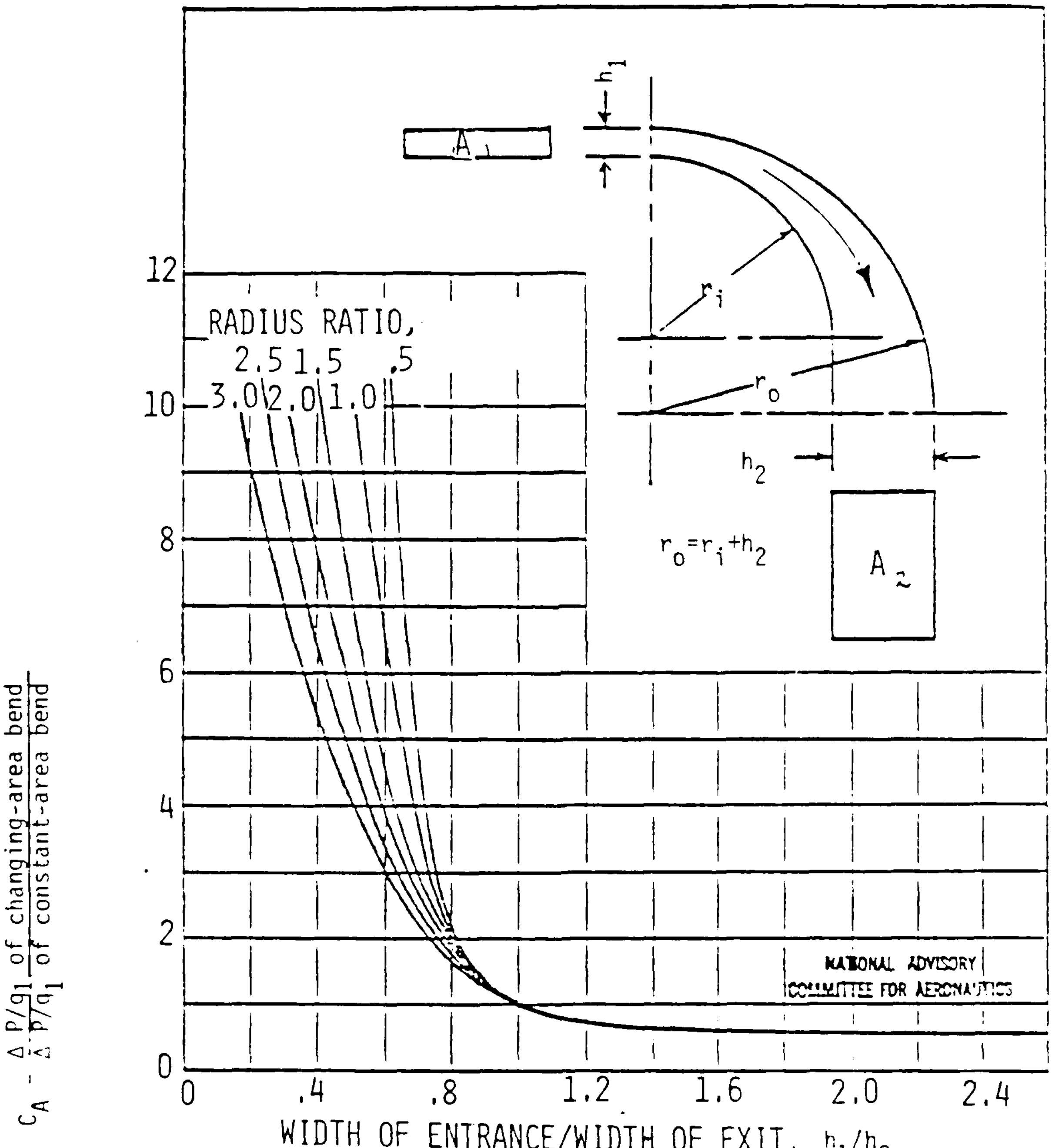



FIGURE 11 TOTAL PRESSURE LOSS COEFFICIENT FOR 90 DEG CIRCULAR-ARC BENDS OF CHANGING AREA. REFERENCE (14)

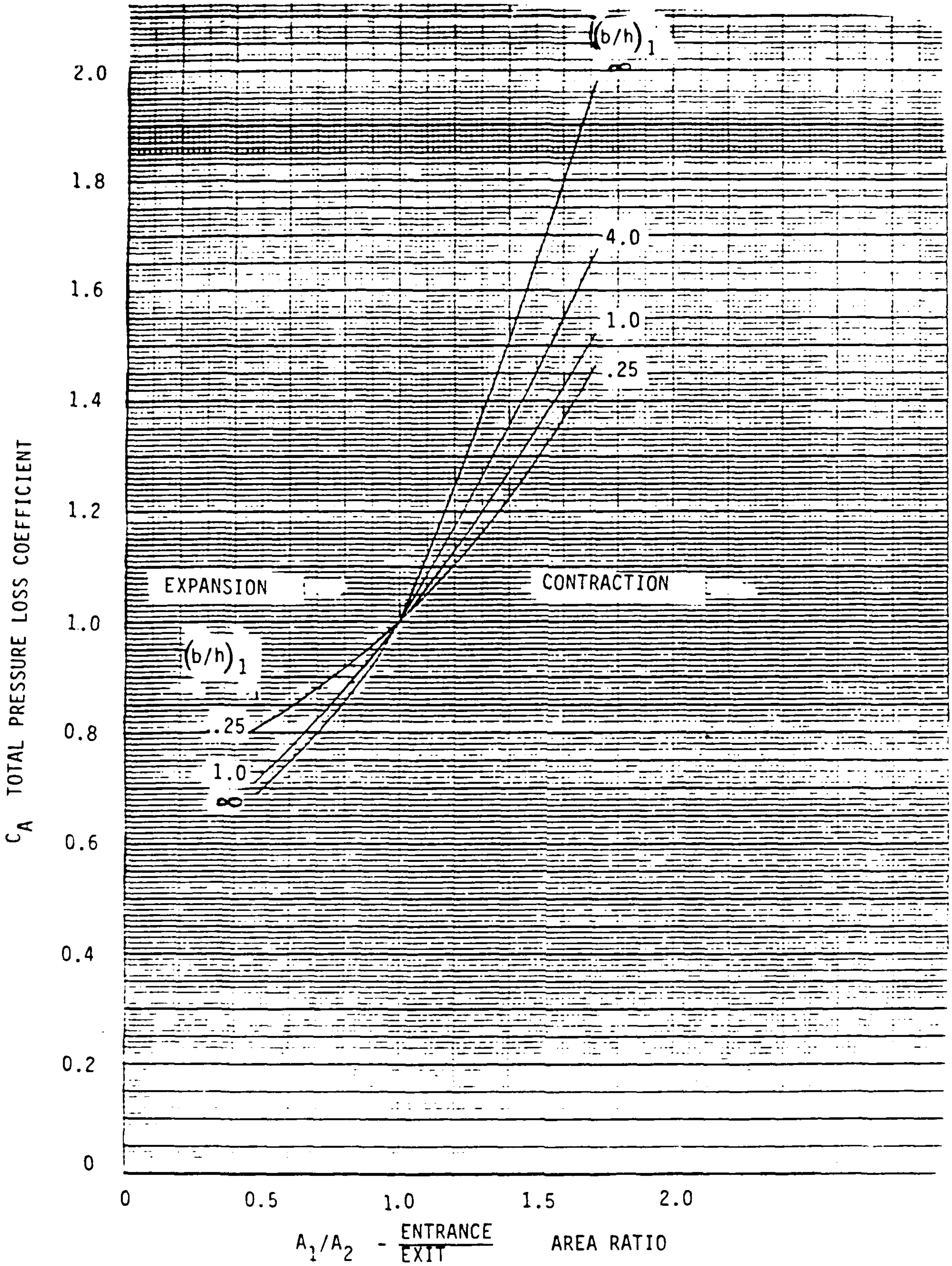



FIGURE 12 TOTAL PRESSURE LOSS COEFFICIENT FOR 90 DEG. MITRE BENDS OF CHANGING AREA. REFERENCE (13)

## IV. TOTAL PRESSURE LOSS COEFFICIENTS FOR BRANCHES

The steady flows through junctions and branches differ from flows through other restrictions discussed in that mass is increased or decreased within the component. Most restrictions constitute series flow losses where the massflow leaving is the same as the massflow entering. However, internal flow systems contain many flow intersections of parallel restrictions where the local dynamics influence the total pressure loss. The flow model for the intersection should include k-factors which account for the effects of mixing in combining flows and diffusion turbulence in dividing flows. These flow processes are generally a function of the flow split, which requires an iterative solution for the correct k-factor. The flow processes in junctions and branches behave like those in bends in many ways, but the additional effects of mixing flows from different sources or delivering flows to different sinks complicate their physical models. Multitudes of junction and branch geometries exist in engineering practice. Two of the most common geometries, symmetrical and unsymmetrical, are shown in Figure 13.

At a junction or a branch, continuity must be satisfied:

$$\dot{m}_3 = \dot{m}_2 + \dot{m}_1$$

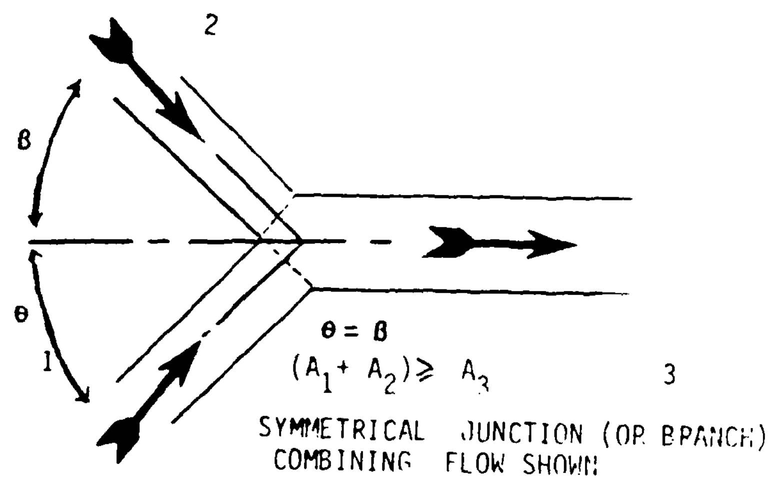
In addition momentum and energy must be conserved:

$$P_3 A_3 + \rho_3 A_3 V_3^2 \simeq (P_1 A_1 + \rho_1 A_1 V_1^2) \cos\Theta + (P_2 A_2 + \rho_2 A_2 V_2^2) \cos\beta$$

where

$$P_1 A_1 \cos\Theta = 0 \quad \text{for the unsymmetrical case}$$

$$\dot{m}_3 c_{p_3} T_3 = \dot{m}_1 c_{p_1} T_1 + \dot{m}_2 c_{p_2} T_2 \qquad \text{(adiabatic)}$$



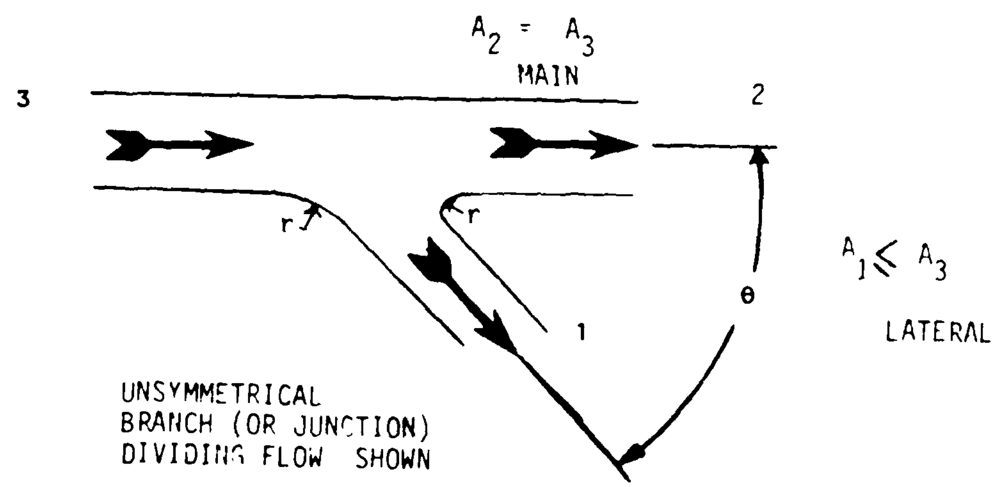




FIGURE 13 COMMON GEOMETRIES FOR JUNCTIONS AND BRANCHES

Vazsonyi (18) attempted the analytical prediction of junction and branch performance on the basis of this physical model utilizing bend flow process analogies. The adaptation of this work for generalized junction and branch k-factors by the SAE (9) was unsuccessful. Although a profusion of pressure loss data exist for a multitude of geometries, the generalization and reduction to usable k-factor parametrics is limited essentially to the basic symmetrical and unsymmetrical varities. Williamson and Rhone (19), however, do present a survey of special geometries.

The k-factors, ${}_nk_3$, have been defined using the dynamic pressure in the limb with the combined flow (leg 3). The k-factor is positive for a total pressure loss or is negative for a total pressure gain. The k-factors presented for junctions and branches do not include the total pressure lost to wall friction. Consequently, the loss model for combining or dividing flows with upstream tangent and downstream tangent at least three hydraulic diameters long should be as follows:

$${}_n\Delta_3 P = {}_nk_3\left(\frac{1}{2}\rho_3 V_3^2\right) + 4f_3\left(\frac{\ell}{D}\right)_3\left(\frac{1}{2}\rho_3 V_3^2\right) + 4f_n\left(\frac{\ell}{HD}\right)_n\left(\frac{1}{2}\rho_n V_n^2\right)$$

Occasionally it is desirable to reference the k-factor to another leg (n),

$${}_3k_n = \left[\frac{\left(\frac{\dot{m}}{A}\right)_3}{\left(\frac{\dot{m}}{A}\right)_n}\right]^2 \left(\frac{\rho_n}{\rho_3}\right) {}_nk_3$$

As for bends, experimental results for circular ducts and square ducts show negligible difference (1). Little influence from Reynolds number is evident in turbulent flow. When the flow is not turbulent, the energy contribution is generally minimal due to small dynamic pressure.

Although the following junction and branch models are based on experiments with fluids at constant densities, the results can be applied to compressible flows with reasonable accuracy.

If more analytical precision is required and the restriction geometry and flow environment warrant, reference (20) for combining flow junctions and reference (21) for dividing flow branches can be used for restriction modeling

## Symmetrical Junctions and Branches

Symmetrical junctions and branches are often referred to as wyes because of their geometrical configuration. The data of Miller (16) correlate well with that of other investigators and are slightly pessimistic. It is ordinarily good design practice to err on the side of high total pressure loss, so the Miller (5) performance maps in Figure 14 were selected for the total pressure loss associated with combining flows in wyes,

$$_1k_3 = \frac{P_1 - P_3}{\frac{1}{2}\rho_3 V_3^2}$$

Similarly, the performance maps by Mille (5) in Figure 15 were preferred for the total pressure loss model of dividing flows in wyes,

$$_1k_3 = \frac{P_3 - P_1}{\frac{1}{2}\rho_3 V_3^2}$$

Another common class of symmetrical junction is the 90° three-way dividing branch or four-way cross. Miller (5) provides k-factor maps, shown in Figure 16, for the perpendicular off-take leg, $_1k_3$, and for the straight-through leg, $_2k_3$. The performance is shown for a dividing junction with all legs of equal area and with sharp edges at the intersections.

## Unsymmetrical Junctions and Branches

Junctions and branches having two of the limbs colinear are frequently encountered in gas turbine internal flow systems. Restrictions interfacing at 90 deg tees are common. The modeling of manifolds is one of the most important applications for such k-factor data. Fortunately, Gardel (22) has done a comprehensive experimental program to determine the effects of

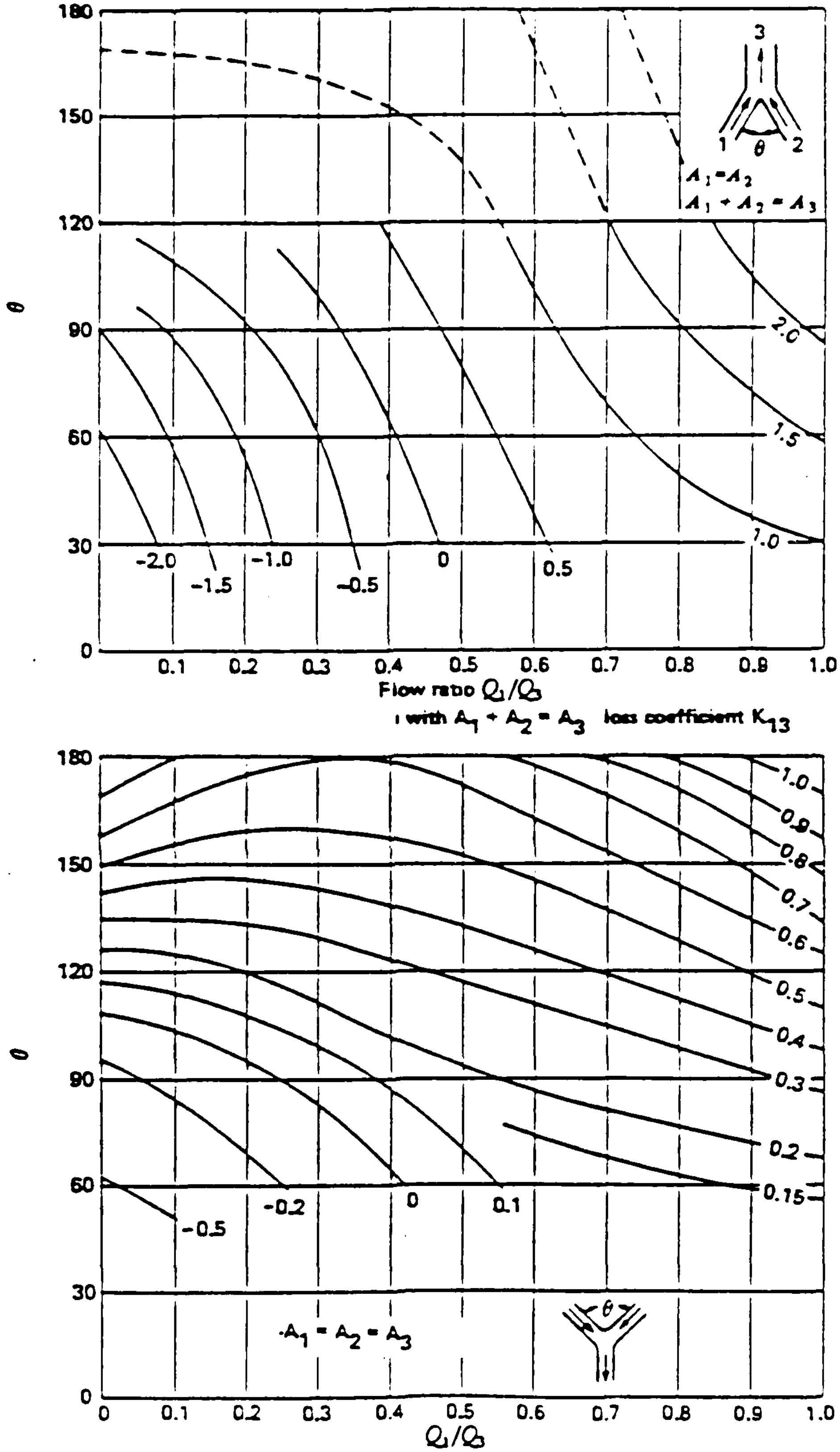



FIGURE 14. COMBINING FLOW—SYMMETRICAL 'Y' JUNCTION
Reference (5)

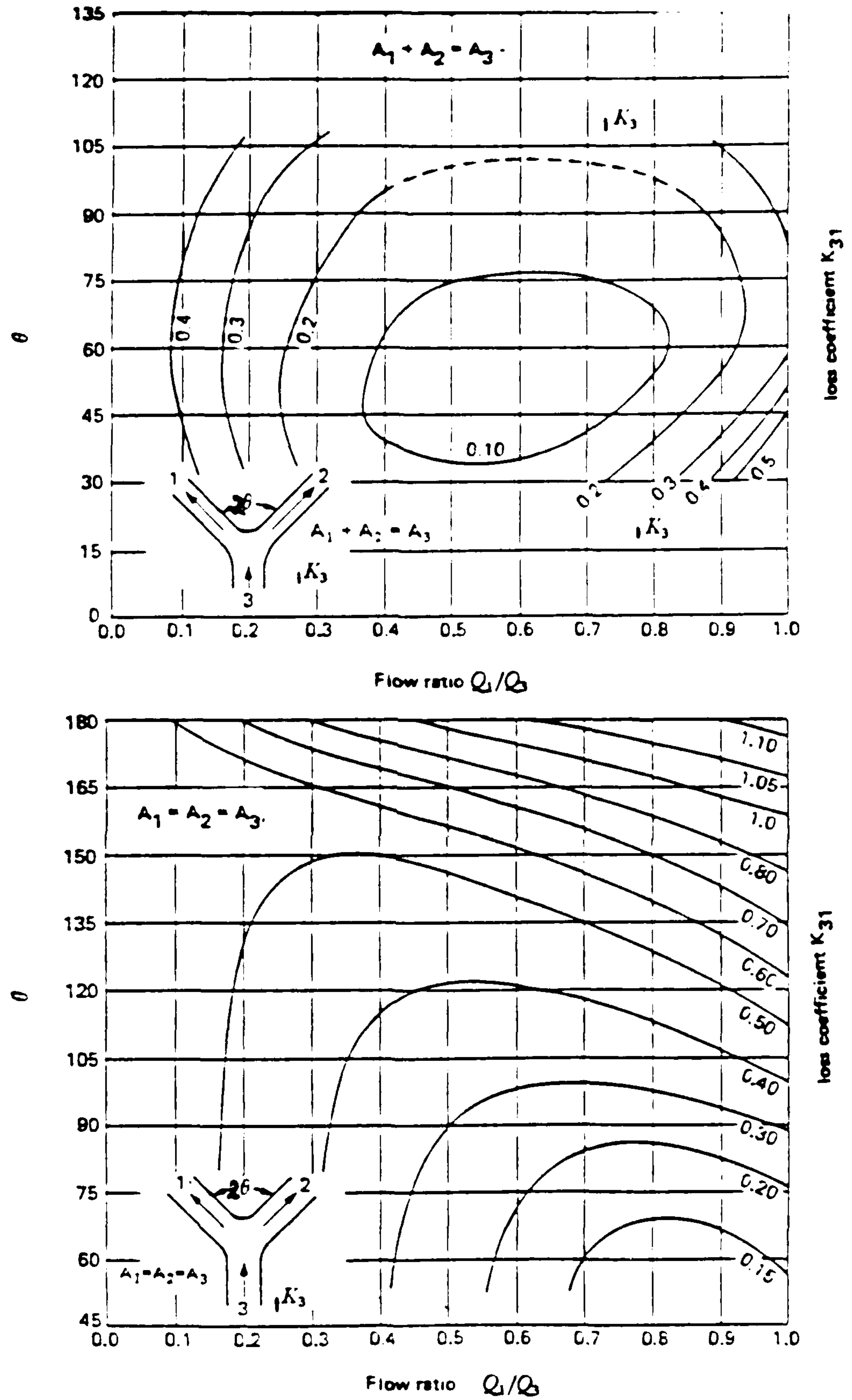
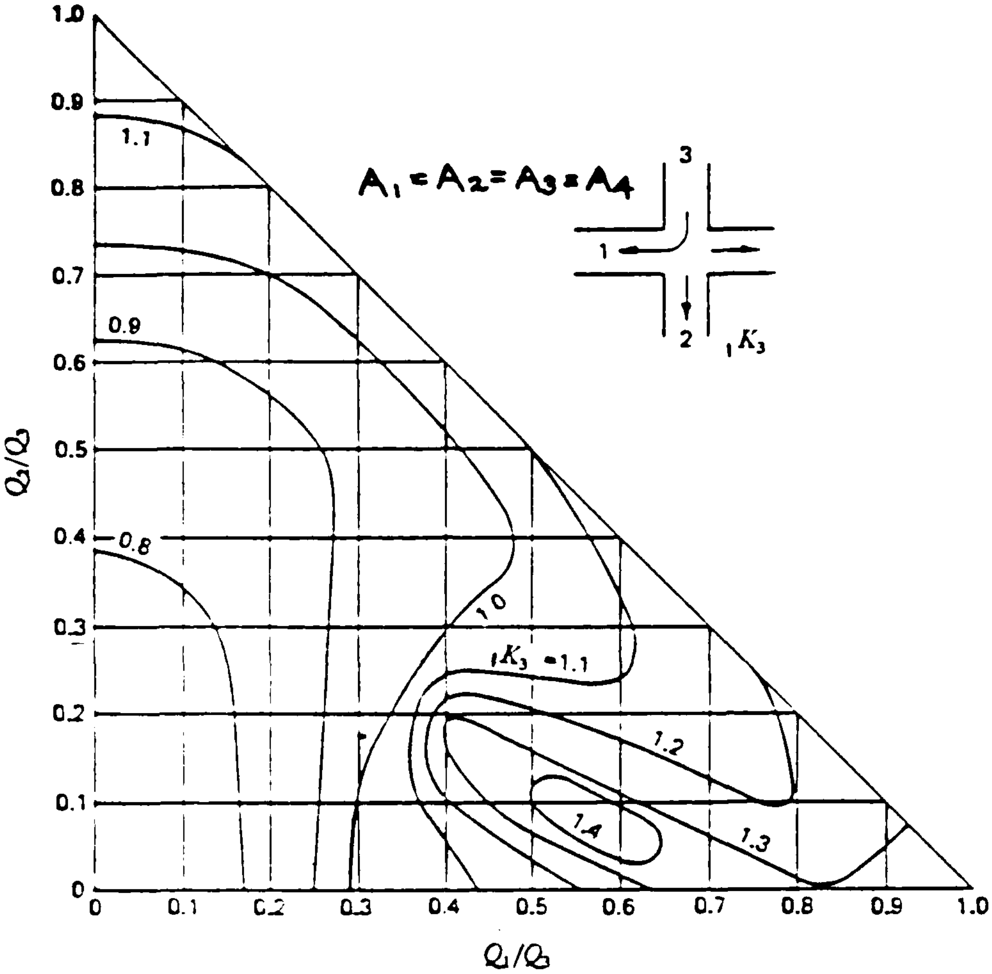
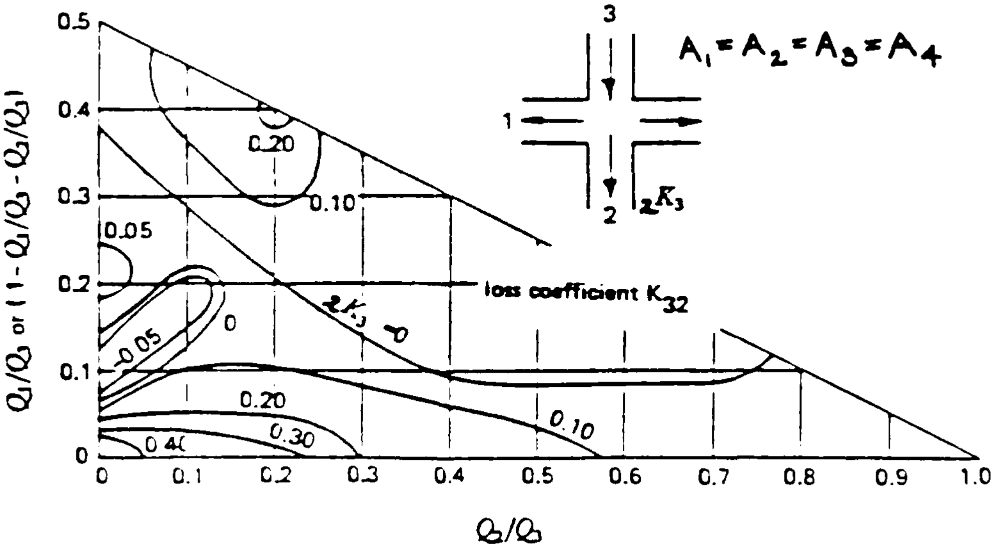



FIGURE 15 DIVIDING FLOW-SYMMETRICAL 'Y' JUNCTION REFERENCE (5)




loss coefficient $K_{31}$




loss coefficient $K_{32}$

FIGURE 16 4-WAY DIVIDING JUNCTION. REFERENCE (5)

changing duct sizes, lateral angles, and introducing fillets and radii at the lateral limb. Gardel derived the following empirical equations to represent the performance of unsymmetrical junctions (combining flow):

$$_1k_3 = -0.92\,(1 - q)^2 - q^2\,[(1.2 - r^{1/2})(\frac{\cos\theta}{a} - 1) \ldots$$

$$\ldots + 0.8\,(1 - \frac{1}{a^2}) - (\frac{1}{a} - 1)\cos\theta] + (2 - a)(1 - q)\,q$$

$$_2k_3 = 0.03\,(1 - q)^2 - q^2\,[1 + (1.62 - r^{1/2})(\frac{\cos\theta}{a} - 1) \ldots$$

$$\ldots - 0.38\,(1 - a)] + (2 - a)\,(1 - q)\,q$$

where

$$_1k_3 = \frac{P_1 - P_3}{1/2\ \rho_3\ V_3^2} \quad \text{and} \quad _2k_3 = \frac{P_2 - P_3}{1/2\ \rho_3\ V_3^2}$$

For unsymmetrical branches (dividing flow):

$$_1k_3 = 0.95\,(1 - q)^2 + q^2\,[(1.3\tan\frac{\theta}{2} - 0.3 + \frac{(0.4 - 0.1a)}{a^2}) \ldots$$

$$\ldots(1 - 0.9\,(\frac{r}{a})^{1/2})] + 0.4\,q(1 - q)\left(\frac{1 + a}{a}\right)\tan\frac{\theta}{2}$$

$$_2k_3 = 0.03\,(1 - q)^2 + 0.35\,q^2 - 0.2\,q(1 - q)$$

where

$$_1k_3 = \frac{P_3 - P_1}{1/2\ \rho_3\ V_3^2} \quad \text{and} \quad _2k_3 = \frac{P_3 - P_2}{1/2\ \rho_3\ V_3^2}$$

In these equations $q = \frac{Q_1}{Q_3}$

for a range of lateral angle $15^\circ < \theta < 165^\circ$

Also $a = \frac{A_1}{A_3}$ $(0.625 < a < 1)$

and $r = \frac{r}{HD_3}$ $(0 < r < 0.12)$

For compressible flows $q = \frac{\dot{m}_1}{\dot{m}_3}$ is preferred.

## V. TOTAL PRESSURE LOSS COEFFICIENTS FOR SUDDEN AREA CHANGES

The most common restrictions encountered in modeling internal flow systems for gas turbine engines are sudden expansions and sudden contractions as illustrated in Figure 17.

The sudden expansion loss is well represented by a one-dimensional analysis. Although the sudden contraction appears to be the geometrical reverse of the sudden expansion, it is not possible to obtain a comparable explicit solution for total pressure loss from a one-dimensional flow model.

### Sudden Expansion

Flow from a duct into a sudden enlargement can be analyzed by conserving mass, momentum, and energy between the discharge plane, $A_1$, and the reattachment plane, $A_2$. Incompressible turbulent flow is well represented by the Borda-Carnot relation

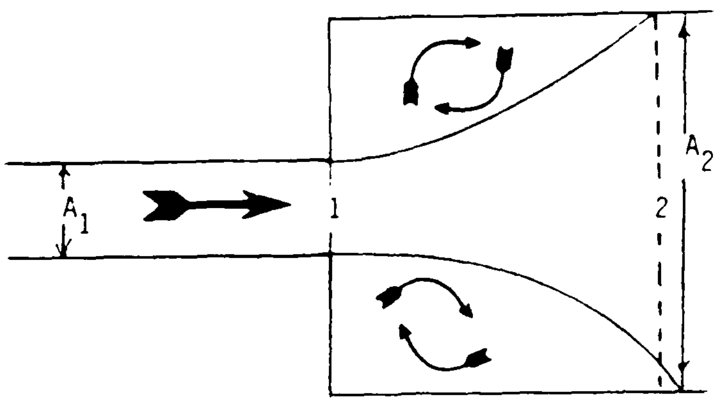
$$k_{se} = \left(1 - \frac{A_1}{A_2}\right)^2$$

where

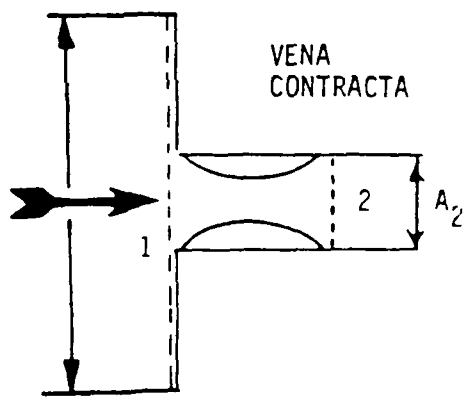
$$_1\Delta_2\, P = k_{se}\, q_1$$

Laminar flow correlates poorly with the one-dimensional equations due to:

- o the large velocity gradients in the profile of the efflux,
- o the important shear stress contribution to reattachment with the possible unsymmetrical flow fields in two-dimensional duct geometries.




SUDDEN EXPANSION




SUDDEN CONTRACTION

FIGURE 17 GENERAL CONFIGURATION OF SUDDEN AREA CHANGES

Adiabatic compressible flow can be modeled similarly as described by Benedict, et. al., (23)

$$\frac{M_2 \left(1 + \frac{\gamma-1}{2} M_2^2\right)^{1/2}}{1 + \gamma M_2^2} = \frac{M_1 \left(1 + \frac{\gamma-1}{2} M_1^2\right)^{1/2}}{1 + \gamma M_1^2 + \left(\frac{p_e}{p_1}\right)\left(\frac{1-\lambda}{\lambda}\right)}$$

where

$p_e$ - static pressure at the face of the step.

When the efflux from duct $A_1$ is subsonic ($0 \le M_1 \le 1$), the flow field in the enlargement is also subsonic ($0 \le M_2 \le 1$) and $p_e/p_1 = 1.0$.

Ward-Smith (1) suggests using a parameter

$$N = \frac{M}{\left(1 + \frac{\gamma-1}{2} M^2\right)^{1/2}}$$

which simplifies the subsonic equation to the recognizable quadratic form

$$N_2^2 - \left\{\frac{2}{(\gamma+1)\ \lambda\ N_1}\left[1 + N_1^2 \left(\gamma\lambda - \frac{\gamma-1}{2}\right)\right]\right\} N_2 + \frac{2}{\gamma+1} = 0$$

Then

$$N_2 = \left(\frac{-b}{2}\right) - \sqrt{\left(\frac{-b}{2}\right)^2 - \left(\frac{2}{\gamma+1}\right)}$$

where

$$-\frac{b}{2} = \frac{1 + N_1^2 \left(\gamma\lambda - \frac{\gamma-1}{2}\right)}{(\gamma+1)\ \lambda\ N_1}$$

and

$$M_2 = \sqrt{\frac{N_2^2}{1 + \frac{\gamma-1}{2} N_2^2}}$$

The total pressure ratio is determined by the expansion geometry and Mach numbers as

$$\frac{P_2}{P_1} = \lambda\left(\frac{M_1}{M_2}\right)\left[\frac{1 + \frac{\gamma-1}{2} M_2^2}{1 + \frac{\gamma-1}{2} M_1^2}\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

Then either the k-factor based on dynamic pressure

$$k_{se} = \frac{1 - \frac{P_2}{P_1}}{\frac{\gamma}{2}\left(\frac{p_1}{P_1}\right) M_1^2}$$

or the k-factor based on impact pressure

$$k^+_{se} = \frac{1 - \frac{P_2}{P_1}}{1 - \frac{p_1}{P_1}}$$

can be calculated.

Singularities are encountered where $A_2$ becomes very large ($\lambda \to 0$) and where $M_1$ becomes very small ($M_1 \to 0$). Noting that $N_2$ and $M_2$ become zero when $\lambda = 0$ for any value of $M_1$, the entire energy in the jet, $(P_1 - p_1)$, is dissipated in the expansion to $p_2 = p_1$. Since $k^+_{se} \equiv 1.0$ at $\lambda = 0$,

$$k_{se} = \frac{1 - (p_1/P_1)}{\frac{\gamma}{2}\left(\frac{p_1}{P_1}\right) M_1^2} \quad \text{at } \lambda = 0.$$

Numerical realities make the use of $k_{se}$ or $k^+_{se} = 1.0$ at $\lambda = 0$ recommended practice for all $\lambda < 0.0001$.

Any compressible fluid flowing adiabatically assumes a constant density character at Mach numbers below 0.1. Consequently, the incompressible Carnot-Borda equation for a sudden expansion loss can be used as the asymptotic value for $k_{se}$ and $k^+_{se}$ at $M_1 < 0.1$.

The relationship between the k-factors based on dynamic pressure or impact pressure are shown in Figure 18 for all subsonic sudden expansions of a perfect gas with $\gamma = 1.4$. Although either k-factor definition is equally accurate, physical conceptualization of the loss as an extension of the incompressible case seems easier based on impact pressure, $k^{+}_{se}$.

When the efflux from duct $A_1$ is supercritical ($M_2 > 1.0$) for the choked condition, $M_1 = 1.0$, the sudden enlargement equation can be solved for the effective step face-to-jet static pressure ratio as a function of $M_2$

$$\frac{p_e}{p_1} = \left(\frac{\lambda}{1-\lambda}\right)\left(\frac{\gamma+1}{2}\right)^{1/2}\left\{\frac{1+\gamma M_2^2}{M_2\left(1+\frac{\gamma-1}{2}M_2^2\right)^{1/2}} - \left(\frac{\gamma+1}{2}\right)^{1/2}\right\}$$

The total pressure loss calculation in this underexpanded flow regime simplifies to

$$\frac{P_2}{P_1} = \frac{\lambda}{M_2}\left[\frac{1+\frac{\gamma-1}{2}M_2^2}{\frac{(\gamma+1)}{2}}\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

An iterative solution can then be performed to determine the $M_2$, $p_e/p_1$ pair compatible with the given duct discharge conditions $P_1$, $p_1$. Assuming a final subsonic Mach number, $M_2 < 1.0$, the terminal conditions must conform to

$$\frac{\dot{m}\sqrt{T}}{P_2 A_2} = \sqrt{\frac{\gamma g_c}{R}}\,\frac{M_2}{\left(1+\frac{\gamma-1}{2}M_2^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}$$

The k-factors for the supercritical sudden expansion can be easily determined from the constant pressure ratio of the jet as

$$k_{se} = \frac{1-\frac{P_2}{P_1}}{0.36980}$$

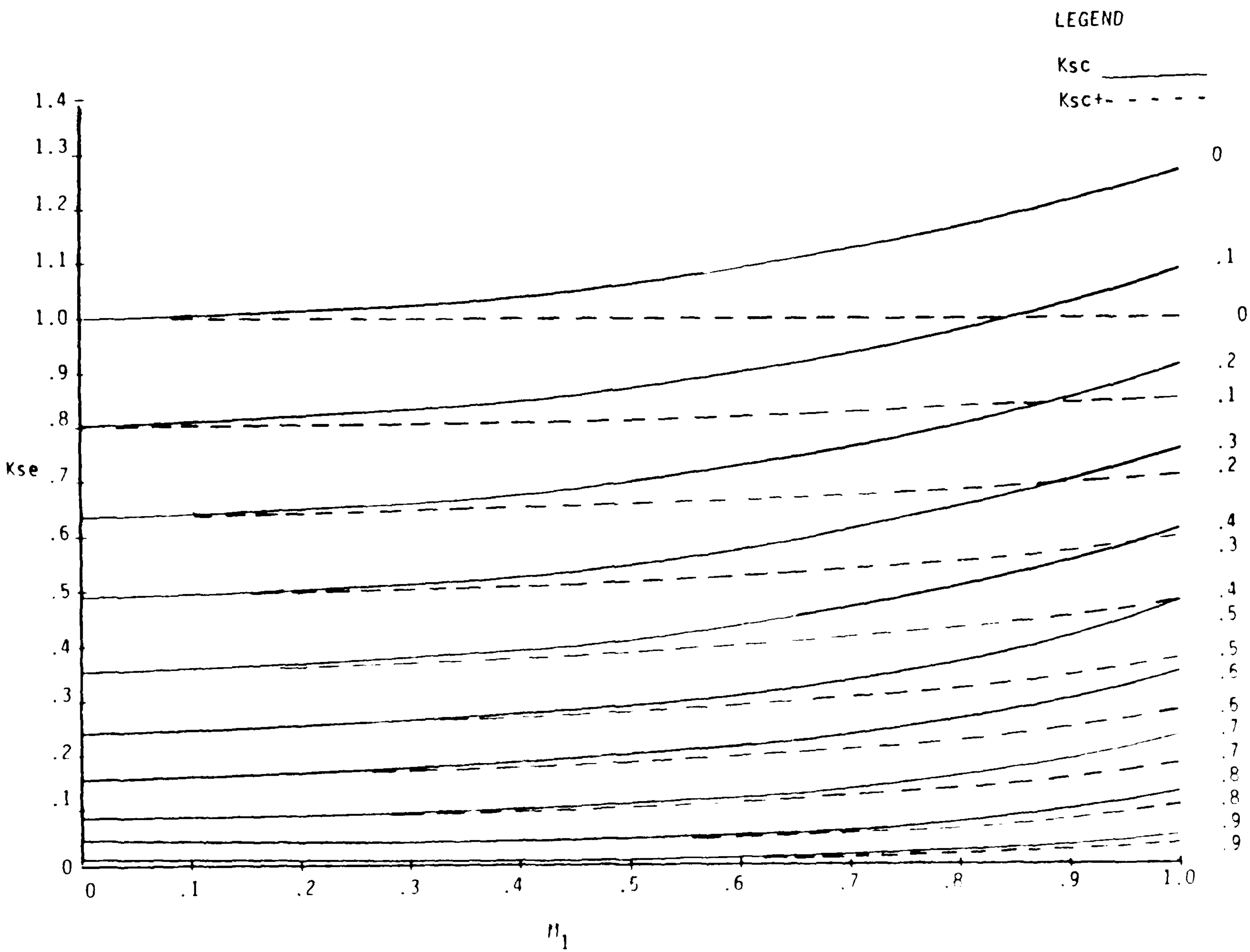
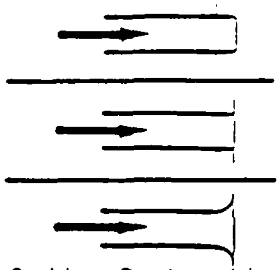



FIGURE 18 SUDDEN EXPANSION OF COMPRESSIBLE TURBULENT FLOW $\gamma$ = 1.40

Since the Borda-Carnot derivation is unconcerned with the duct shape, the quality of fit for the sudden expansion model indicates that duct shape is a secondary effect, as shown in Table IV. Variations in the discharge port geometry have a negligible effect on the sudden expansion loss. Even gradually expanding ducts with divergence angles exceeding about 45° experience flow separation which behaves essentially like an abrupt enlargement. The concept can be extended to include the separated flow (vena contracta) at sharp-edged entrances or forward facing steps. The physics of the sudden expansion model are helpful in understanding the modeling of the k-factors for sudden contractions and sharp-edged orifices.

Table IV.
Loss k-factor for pipe exits. Reference (24)



| Fitting | Description | k-factor |
|---|---|---|
| | Projecting | 1.0 |
| | Sharp edged | 1.0 |
| | Rounded | 1.0 |

Sudden Contraction

Many investigators have studied the flow modeling of a duct entrance from a fluid reservoir or an abrupt area reduction within a duct. Adiabatic flow from an infinite reservoir into a re-entrant duct (Borda mouthpiece), Figure 19, can be accurately modeled one-dimensionally by conserving mass, momentum, and energy between the fluid reservoir and the vena contracta,

$$C_c = \frac{\left(1 + \frac{\gamma-1}{2} M_c\right)^{\frac{\gamma}{\gamma-1}} - 1}{\gamma M_c^2}$$

where

$$\lim_{M_c \to 0} C_c = \frac{\left(1 + \frac{\gamma-1}{2} M_c^2\right)^{\frac{1}{\gamma-1}}}{2} = \frac{1}{2} \qquad \text{or} \qquad k^{+}_{se} = \frac{1 - \frac{P_2}{P_1}}{0.47172}$$

for $\gamma = 1.4$.

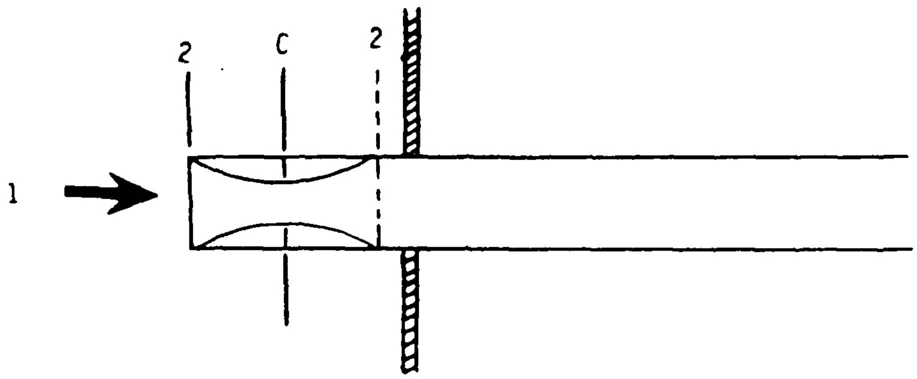



FIGURE 19 RE-ENTRANT INLET IN A FLUID RESERVIOR

The total pressure loss in this type of entering (accelerating) flow is relatively small because the conversion of pressure to velocity (as in a nozzle) is a stable process. Consequently, the assumption of inviscid flow between the reservoir (station 1) and the vena contracta (station c) is appropriate. Then the sudden expansion model for compressible adiabatic flow can be employed to evaluate the total pressure loss for flow reattachment. This modified Hughes and Safford analysis predicts a $1.0 < k_{sc} < 1.095$ range for compressible flow into a Borda mouthpiece. Dodge (24) reports a range of k-factors from 0.68 to 2.5 for incompressible flow depending upon inlet edge conditions (modified corners to sharp). This large discrepancy with empirical k-factor values suggests a shortcoming of the one-dimensional analysis as it applies to sudden contraction losses. The marked curvature of the vena contracta flow compromises the accuracy of the one-dimensional assumption.

As the re-entrant length of the tube decreases to zero, the Borda mouthpiece is transformed into a sharp-edged inlet. The entrance flow no longer develops in isolation from the reservoir wall, so the momentum analysis must be modified. Reaction of the flow with the wall assists turning, and the incompressible contraction coefficient increases to about 0.6. Miller (5) provides dramatic data for this effect as tube wall thickness increases for a re-entrant inlet. The momentum equation no longer defines the total pressure loss explicitly. The Hughes and Safford equation

$$k_{sc} = \frac{1}{C_v^2 C_c^2} - \frac{2}{C_c} + 1$$

predicts $k_{sc} = 1.00$ for a Borda mouthpiece and $k_{sc} = 0.56$ for a sharp-edged inlet from the flow characteristics in Table V.

Table V.
Characteristics for incompressible flow in duct entrances and exits. Reference (25)

| Restriction | $C_v$ | $C_c$ | $C_D$ |
|---|---|---|---|
| re-entrant inlet | 0.98 | 0.52 | 0.51 |
| sharp-edged entrance | 0.80 | 1.00 | 0.80 |
| duct discharge | 1.00 | 1.00 | 1.00 |

Benedict, et. al., (26) propose a generalized equation based on discharge coefficient to more accurately represent sudden contraction losses in constant density flows with an approach velocity

$$k_{sc} = \left(\frac{1}{C_D^2} - 1\right)\left[1 - \left(\frac{A_2}{A_1}\right)^2\right]$$

If $A_2/A_1$ is taken to represent $C_c$ for a re-entrant inlet, $k_{sc} = 2.08$ is predicted, which better represents the empirical value. A $k_{sc} = 0.56$ is still predicted for a sharp-edged entrance where $A_1$ is very large with respect to the duct area. If a baseline total pressure loss coefficient is defined for a sudden contraction as

$$k^*_{sc} = \frac{1}{C_D^2} - 1 \quad ,$$

then the influence of the contraction ratio can be formulated as

$$k_{sc} = k^*_{sc}\left[1 - \left(\frac{A_2}{A_1}\right)^2\right]$$

In many composite restrictions the flow at the entrance or through a sudden contraction occurs at nearly constant density. Then, for most practical applications to gas turbine internal flow systems, an incompressible equation is sufficiently accurate. For $\Lambda < 0.3$, which includes most entrances and many sudden contractions within restrictions, the recommended equation is

$$k_{sc} = 0.5781\ (1 - \Lambda^2)$$

If more accuracy is required or when $\Lambda > 0.3$, the least squares curve fit from the test data of Benedict, et. al, (26) should be used

$$k_{sc} = 0.57806 + 0.39543\ \Lambda^{1/2} - 4.53854\ \Lambda \ldots$$
$$\ldots + 14.24265\ \Lambda^{3/2} - 19.22214\ \Lambda^2 + 8.54038\ \Lambda^{5/2}$$

These data represent sudden contraction characteristics for constant density flow into long ducts where complete reattachment is assured. If the duct contraction length is short, $(\ell/HD)_{sc} < 3$, the "long hole" correction presented under orifice restrictions should be applied to $k_{sc}$. The effect of compressibility increased the experimental value for $k_{sc}$ as much as 12% for subsonic flow (26). Considering the uncertainties associated with data, installation, and environment the constant density model for sudden contractions is justified.

The sudden contraction model discussed so far applies only to tubes or entrances which are aligned with the approaching flow and have sharp inlet edges. Figure 20 provides corrections obtained for entrances oblique to the approaching flow. One curve applies to a sudden contraction with the downstream duct normal to the step or wall which is at an angle to the approaching flow. The other curve applies to a sudden contraction with the downstream duct at an angle to the step or wall which is perpendicular to the approaching flow. Figure 21 provides a correction factor which accounts for rounding or edge break effects on sudden contraction characteristics. Then the general contraction coefficient can be found as:

$$k_{sc} = C_a \, C_r \, k^{*}_{sc} \, (1 - \Lambda^2).$$

If better analytical precision is required, reference (27) for sudden duct enlargements and reference (28) for sudden duct contractions can be used for restriction modeling.

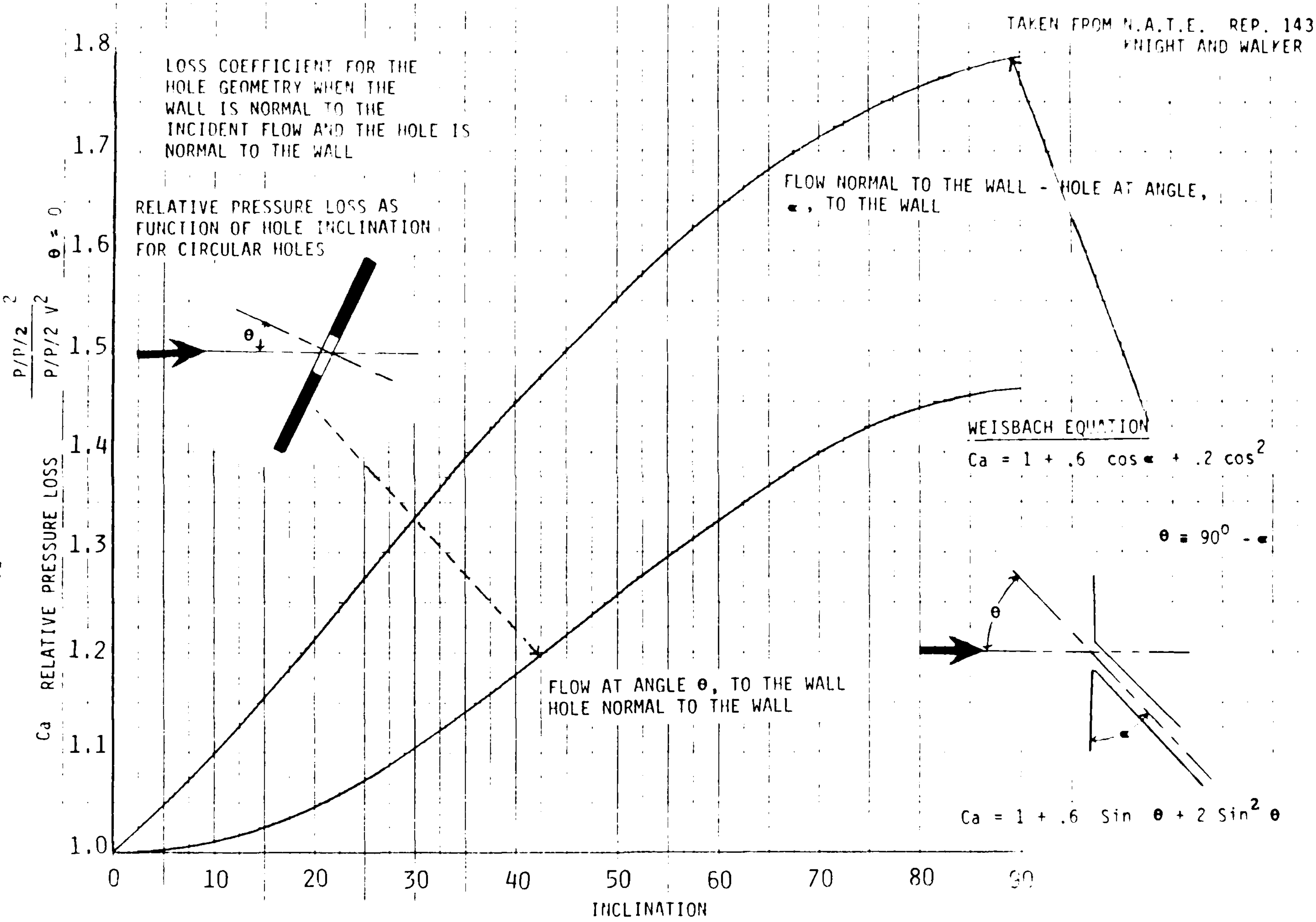



FIGURE 20 EFFECT OF ORIFICE AND INLET ANGULARITY WITH RESPECT TO APPROACH FLOW. REFERENCES (8) AND (13)

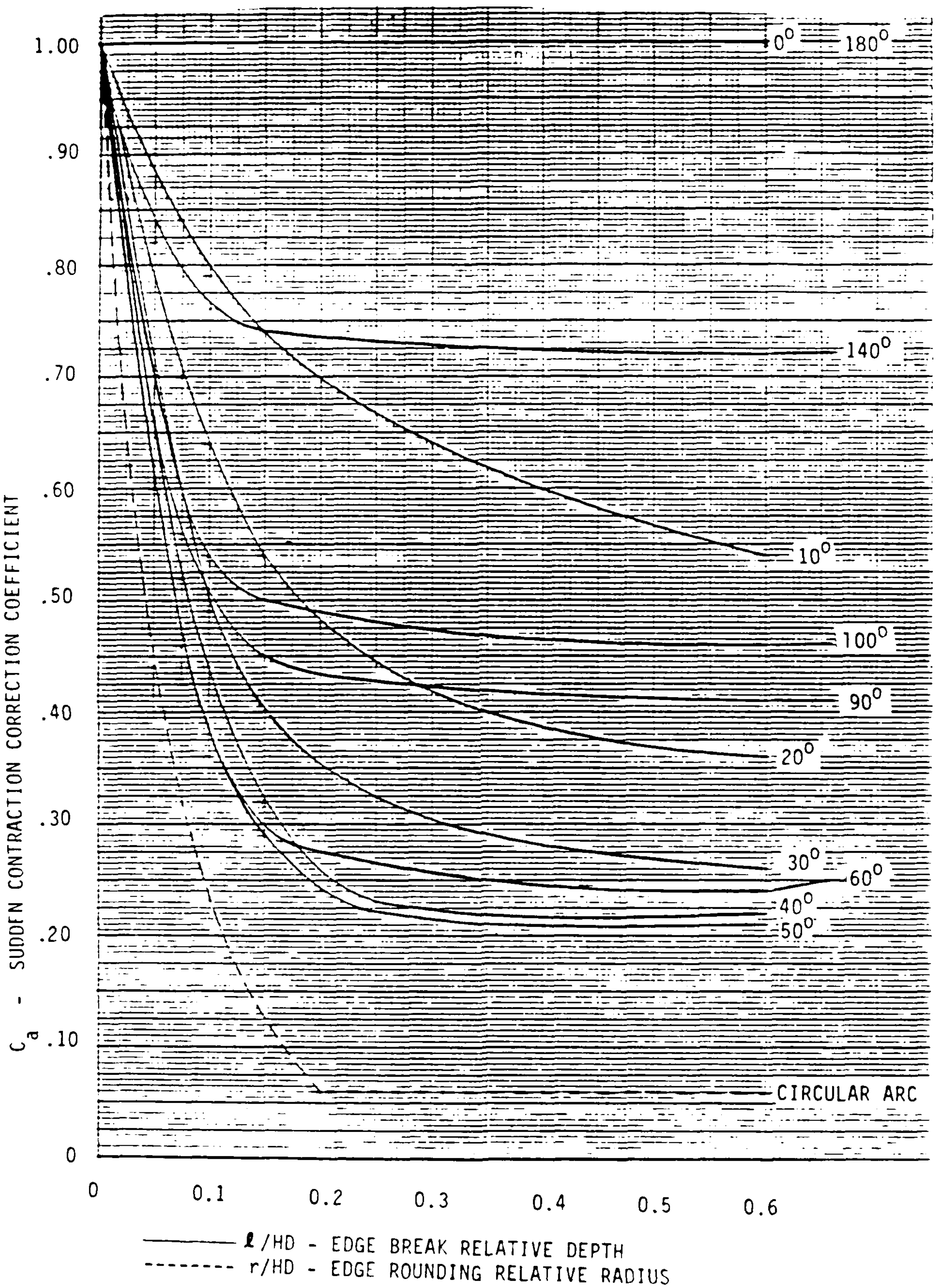



FIGURE 21 EFFECT OF INLET EDGE CONDITION ON SUDDEN CONTRACTION LOSS. REFERENCE (13)

## VI. TOTAL PRESSURE LOSS COEFFICIENTS FOR ORIFICES

Orifice type restrictions in gas turbine internal flow systems ordinarily consist of a thin end wall through which a hole permits flow communication between considerably larger upstream and downstream ducts. The inlet to an orifice is abrupt and relatively sharp so that significant flow separation results. A typical orifice is diagrammed in Figure 22.

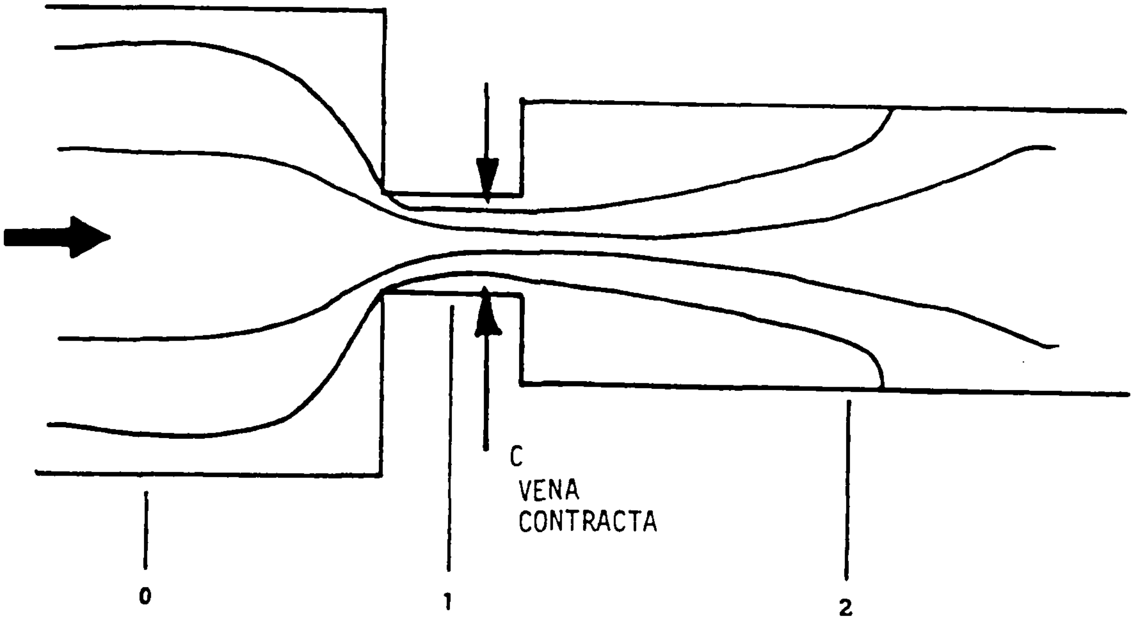



FIGURE 22. SCHEMATIC FOR A TYPICAL ORIFICE RESTRICTION.

The flow characteristic that distinguishes an orifice from a long hole or a nozzle is the inability of the vena contracta, which is induced by the sharpness of the sudden contraction, to isolate itself by flow reattachment to the wall before the sudden expansion. Consequently, the orifice flow model must combine a sudden contraction and a sudden expansion which are modified to account for interactions with the special flow processes that occur at the entrance and the exit. The conventional procedure has been to add a modifying k-factor, $k_\ell$, which incorporates the interactive effects of upstream and downstream duct geometry with the correction required to account for the sustained separation of the flow through the hole. Consideration of the small wall friction loss can be included. Since the complex flow processes in the formation and disolution of the vena contracta are only qualitatively understood, the orifice model is based upon empirical correlations for

$$k_\theta = k_{sc} + k_\ell + 4f\,\ell/HD + k_{se}$$

When the length of the small hole connecting a sudden enlargement is less than three hydraulic diameters, the vena contracta formed at the entrance to the orifice may not reattach within the short length. Without reattachment the sudden contraction becomes sensitive to flow conditions in the downstream enlargement. Separated flow at the orifice exit does not conform to the model established for a sudden expansion. An orifice model for incompressible flow to account for the process interactions caused by separtion was derived by Dodge (24):

$$k_{sc} = k^*_{sc}\,[1-\Lambda] \qquad \text{where } k^*_{sc} = 0.5$$

$$k_\ell = k^*_\ell\,[k_{sc}\,k_{se}]^{1/2} \qquad \text{where } k^*_\ell \text{ is defined by Figure 23}$$

$$k_{se} = k^*_{se}\,[1-\lambda]^2 \qquad \text{where } k^*_{se} = 1.0$$

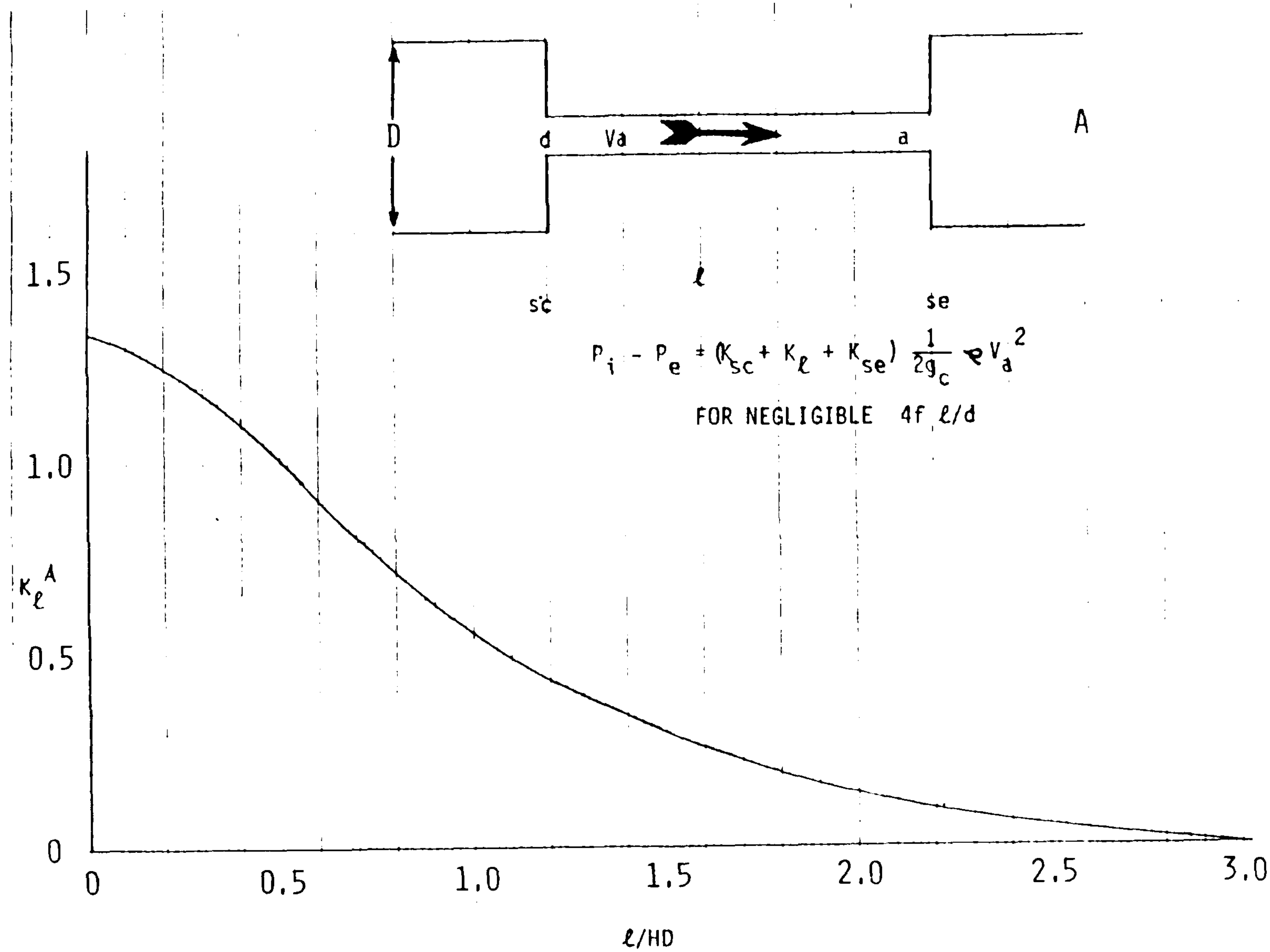



FIGURE 23 LONG HOLE EFFECT. REFERENCE (24)

The vena contracta loss for incompressible flow through thick static orifices is evaluated by the empirical $k_\ell^*$ of Figure 23. The influence of approach velocity and limited downstream expansion on the severity and extent of separation is corrected by

$$k_\ell = k_\ell^* \, [1-\Lambda]^{1/2} \, [1-\lambda]$$

The performance of orifices is buffered against effects from adjacent restrictions or tangent geometry by 1.5 hydraulic diameters or more of straight duct. The orifice characteristics are unaffected by Reynolds numbers in the hole that are greater than 1 $(10^5)$.

Fluid compressibility exerts the strongest influence on high velocity flow through orifices. Contrary to the invariant behavior of the vena contracta of incompressible flow, the separation process is a function of the orifice pressure ratio in a compressible flow. The level of separation decreases as the pressure ratio, r, decreases. Although the expanded vena contracta area reduces the extent of the separated flow, the orifice losses with compressible flow are not decreased.

The most familiar characteristic of compressibility associated with orifice performance is shown in Figure 24. The flow through orifices differs from that through most restrictions in the supercritical behavior. When a typical restriction becomes critical ($M = 1.0$ at some flow location), the flow parameter, $\Phi$, is maximized with respect to pressure ratio. The restriction is said to be choked at that location. Then the adiabatic flow rate becomes linearly dependent upon upstream total pressure, but independent of further reductions in restriction pressure ratio, r. On the contrary, however, an orifice can be critical at its vena contracta ($M_c = 1$) and still exhibit an increasing flow parameter, $\Phi$, as the pressure ratio, r, is reduced. This behavior results from the influence that the downstream static pressure exerts on the "free-jet" vena contracta. In highly separated flows like those encountered with sharp-edged contractions and flow angularity, these compressibility effects become exaggerated for thin (short duct) orifices.

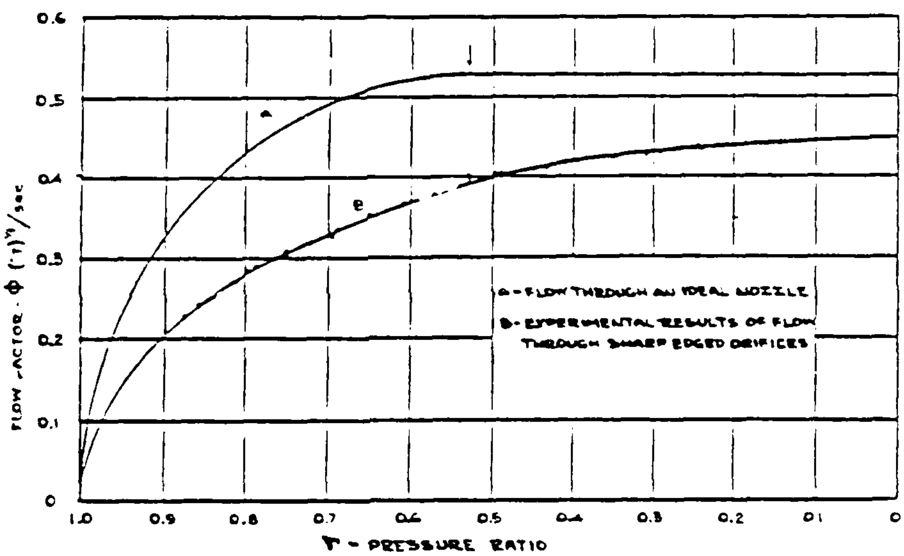



FIGURE 24  FLOW THROUGH SHARP-EDGED ORIFICES COMPARED TO FLOW THROUGH AN IDEAL NOZZLE. (REFERENCE (29)

for thicker orifices in coaxial flow, the vena contracta environment is isolated from the downstream static conditions. For short holes with an $\ell/D > 4$ choking will rarely occur at the vena contracta. In any event, thick orifices and relatively large orifices, where small area changes reduce the separation, are less sensitive to the supercritical compressibility effects. Small edge-breaks or leading edge radii radically suppress separation. The geometry of an orifice:

sudden contraction ratio, $A_1/A_o = \Lambda$
inlet flow angularity, $C_a$
leading edge sharpness, $C_r$
orifice thickness, $\ell/HD$
sudden expansion ratio, $A_1/A_2 = \lambda$

affects orifice performance in either incompressible or compressible flows. However, the orifice pressure ratio only influences the performance of orifices in compressible flow[4]. The greatest effect is seen on thin, static orifices operating in or near the supercritical regime.

## Synthesis of an Orifice Model

Orifices encountered in gas turbine internal flow systems can encompass any combination of geometric variables important to flow capacity, Figure 25. Therefore, a comprehensive model for orifice flow characteristic prediction is required. The model proposed by Dodge (24) is amenable to modifications to achieve this flexibility:

$$k_O = k_{sc} + k_\ell + 4f\ (\ell/HD) + k_{se}$$

### Sudden Contraction

$$k_{sc} = C_a\ C_r\ k^*_{sc}\ [1-\Lambda]$$

where flow angularity correction is provided by $C_a = j\ (\theta,\ \text{flow direction})$, Figure 20, and leading edge sharpness correction is provided by $C_r = y\ (\alpha,\ \ell_{sc}/HD)$ for chamfers or $C_r = z\ (r/D)$ for radii from Figure 21.

[4]Cavitating effects can be important in liquid flows.

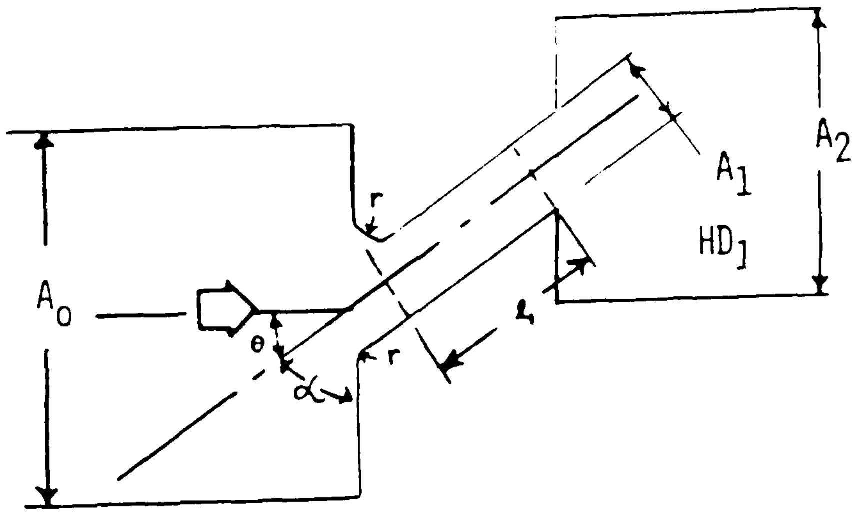



FIGURE 25 GENERALIZED ORIFICE

The sudden contraction model for orifice applications is based on the experimental work of Weisbach testing short orifices and Freeman testing nozzles with water. Both of these investigators obtained contraction coefficient and discharge coefficient data which resulted in

$$k^{*}_{sc} = 0.5 \quad \text{for small } \Lambda.$$

Notice that the sudden contraction model is not the same model selected from reference (26). The sudden contraction data acquired by Benedict, Carlucci, and Swetz were for entrances to long ducts where separation reattachment and velocity profile recovery were attained.

## Vena Contracta

The "long hole" k-factor employed by Dodge (24) corrects for the interactions of contraction and expansion geometry with the incompressible free-jet vena contracta

$$k_{\ell} = (C_a C_r)^{1/2} \; k^{*}_{\ell} \; [1-\Lambda]^{1/2} [1-\lambda]$$

where $k^{*}_{\ell}$ is given for a static orifice by Figure 23.

## Sudden Expansion

The sudden expansion model of Carnot-Borda is used as recommended for incompressible flow

$$k^{+}_{se} = k^{*}_{se} \; [1-\lambda]^{2}$$

where

$$k^{*}_{se} = 1.0$$

The application of the sudden expansion k-factor to the impact pressure, P-p, at the orifice exit, rather than the dynamic pressure recommended for the sudden contraction and vena contracta losses, generalizes the expansion process to the compressible flow regime. This approximation is very good for small expansion ratios.

Although the Dodge (24) model for orifice characteristics is specifically for incompressible flow, it can be applied to certain thick and/or large hole orifices in compressible flow with good accuracy. A technique has been developed to adapt it to thin, small orifices where compressibility effects are most pronounced.

<u>Orifice Characteristics for Compressible Flow</u>

The thin plate, $\ell/D < 0.1$, static orifice, $\Lambda = \lambda < 0.1$, is the most familiar category that exhibits strong compressible flow effects near and in the supercritical regime. It can be demonstrated numerically, however, that small blunting of the leading edge, slight lengthening of the hole ($\ell/D > 1.2$), or restricting the contraction and/or expansion ratio can mitigate the compressible vena contracta characteristic quite rapidly. Consequently, a relatively limited range of orifice geometry requires a more sophisticated compressible flow analysis than that provided by the Dodge model. The extension of the Dodge model to these special orifice flows and the range of applicability will be discussed.

Perry (29) demonstrated that highly separated compressible flow through thin-plate, static orifices behaves linearly in the subcritical region

$$\Phi = \sqrt{m\ (1-r^2)}$$

when modeled in elliptical coordinates

$$\Phi = m\,\Upsilon$$

where m = 0.216 for air. Perry (29) represented the supercritical region as

$$\Phi = (a + nr)\sqrt{1-r}$$

which in elliptical coordinates becomes

$$\Phi = (a + n\sqrt{1-r})^2 \; (1 - \sqrt{1-r})$$

where a = 0.449 and n = 0.241 for air.

The slope of the supercritical flow model was found to be 88% of the subcritical model slope at the choking pressure ratio,

$$m_c^* = 0.88 \; m$$

The compressible flow model proposed by Perry (29) for thin, static orifices can be generalized to model the limited range of orifices where vena contracta compressibility is important, Table VI. The orifice model by Dodge can be used to generate the incompressible flow characteristics for the specific orifice geometry desired.[5] A common slope for the compressible and the incompressible flow can be found near r = 0.87 as

$$m = \left(\frac{\Phi}{r}\right)_{r \sim 0.87}$$

Then

$$n = \sqrt{\frac{\Phi^*}{1-r^*}} \left\{ \frac{1}{1-r^*} \left[ \frac{1}{2} - 0.88 \left( \frac{r^*}{1+r^*} \right) \right] \right\}$$

and

$$a = \sqrt{\frac{\Phi^*}{1-r^*}} - nr^*$$

where

$$r^* = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)} \quad \text{for } \gamma = 1.4$$

and

$$\Phi^* = m \; [1-(r^*)^2].$$

[5] A flow characteristic curve generator similar to DU1 in BC88 PLUS can be used to solve for $\Phi$ at r using the k-factors from the Dodge orifice model.

Table VI.

Applicable range of the compressible flow parameters for orifice models based on Perry (29).

$k_{sc} > 0.4$

$k\ell > 0.65$

$\lambda < 0.125$ which is the same as ($k^{+}_{se} > 0.765$)

$m < 0.26$

It can be seen from the supercritical orifice model that $a = \Phi$ when $r = 0$. Therefore, $a > 0.532$ for air cannot be allowed.

Other more stringent flow modeling restrictions place tighter limits on the applicable range of parameters. The entrance flow must be severely separted, and the orifice hole must be short enough to preclude flow reattachment within the hole. The orifice exit area ratio must provide a large expansion so that the flow reattaches in the far downstream field of the tangent duct. If these stipulations as quantified in Table V are met, the compressible flow characteristics of the orifice can generally be modeled satisfactorily over the complete range of pressure ratio as outlined.

## Example Calculations for Generalized Orifice Flow Characteristics

Two orifices have een modeled to demonstrate the calculation procedures for

1) A conventional thick-plate orifice with nozzle-like characteristics.
2) A generalized thin orifice with definite vena contracta compressibility characteristics.

The detailed calculations for restriction 1 and restriction 2 are located in the Derivations section of the Appendix. The Allison Gas Turbine Engines version of a flow characteristic curve generator program titled DU1 was utilized to calculate the airflow parameter, $\Phi$, as a function of the total pressure ratio, $P_U/P_D$. Constant values for restriction k-factors were used with the exception of the FANNO wall friction calculation. The Moody

correlation for Fanning friction factor was calculated at each flow condition on the curve.

Restriction 1 is nozzle-like according to the low internal k-factors. The flow characteristic curve generated by DU1 calculations of the Dodge model represents the thick-plate orifice performance very well. This orifice will exhibit a classical choked flow characteristic because of the minimal entrance separation and the internal flow reattachment.

Restriction 2 exhibits definite thin orifice-like performance according to the combination of high k-factors for the loss elements and relatively low slope in the elliptical parameters. Since sustained entrance flow separation with free jet vena contracta characteristics are indicated, the flow curve will not choke but will continue to rise in the supercritical regime. Therefore, the Perry model was used to predict the orifice flow curve. The Dodge model was calculated in the DU1 program to determine the orifice baseline performance in the low pressure ratio, $P_U/P_D$, or "incompressible" regime.

The orifice flow characteristics are derived directly from the component loss k-factors in the DU1 calculation. However, if a curve of k-factor versus flow parameter is required for inserting an orifice into a component restriction of a more extensive geometry, the "kurve" data can be developed from the flow curve at each $P_U/P_D$ as follows:

$$\Phi \rightarrow \left(\frac{g}{p}\right)_1 \qquad \text{(see note)}$$

$$k = \frac{1 - (P_D/P_U)}{\left(\frac{g}{p}\right)_1}$$

The "kurve 1" in the example DU1 input is the Perry static orifice curve of k factor versus flow factor, $\Phi$. This data file contains all of the elements for orifice modeling using the procedures of Dodge, Perry, or "k curve".

Note

The calculation of $\left(\frac{q}{p}\right)_1$ from $\Phi$ requires the solution of the implicit equation

$$\Phi = \sqrt{\frac{\gamma g_c}{R}} \frac{M}{\left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}$$

for Mach number. The $\left(\frac{q}{p}\right)_1$ can be found directly from

$$\left(\frac{q}{p}\right)_1 = \frac{\gamma}{2} \frac{M^2}{\left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}}$$

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- Turns and Bends
- Branches--Dividing/Combining
- Sudden Area Changes
- Orifices--Static and Rotating
- Theoretical/Empirical Analysis
- Literature Surveys

Consequently, some of the references appear in more than one category.

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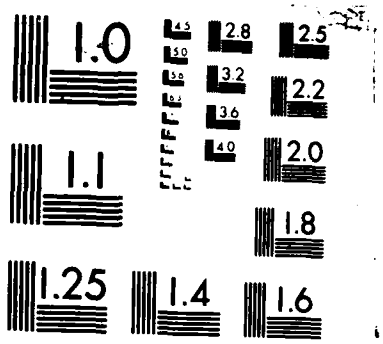


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## NOMENCLATURE

| | |
|---|---|
| $a$ | Small or minor dimension of a cross-section of a rectangular or elliptical duct, in. |
| $a$ | Limiting $\Phi$ of an orifice at $r = 0$ |
| $\mathcal{A}$ | Area ratio, $A_n/A_3$ |
| $A$ | Cross-sectional area of a duct, in.$^2$ |
| $A_{ref}$ | Real or defined reference area for a flow restriction, in.$^2$ |
| $b$ | Large or major dimension of a cross-secton of a rectangular or elliptical duct, in. |
| $c_p$ | Specific heat of the air at constant pressure, Btu/lbm deg R |
| $c_v$ | Specific heat of the air at constant volume, Btu/lbm deg R |
| $C_a$ | Angularity correction for obliquely incident flow into a restriction |
| $C_A$ | Area change correction for bends |
| $C_c$ | Contraction coefficient, $A_c/A_n$ |
| $C_d$ | Drag coefficient |
| $C_D$ | Discharge coefficient for a restriction, $m/m_{id}$ |
| $C_f$ | Frictional influence coefficient for aerodynamically rough wall |
| $C_g$ | Cross-sectional area geometry correction |
| $C_1$ | Influence coefficient for a general parameter which is different than that for the reference restriction |
| $C_\ell$ | Downstream tangent correction |
| $C_M$ | Compressibility influence coefficient for high velocity flow |
| $C_r$ | Edge break correction for a restriction area reduction |
| $C_v$ | Velocity coefficient for a restriction, $V/V_{id}$ |
| $d$ | Diameter of a circular cross-section, or small diameter of an annular cross-sectional area of a duct, in. |
| $D$ | Large diameter of an annular cross-sectional area of a duct, in. |
| $f$ | Fanning friction factor for flow in straight ducts |

NOMENCLATURE (con't)

$f_c$ Darcy-Weisback friction factor for flow in curved ducts

$f(\ )$ Functional relationship of independent variables ( )

$F_d$ Aerodynamic drag force, lbf

$g_c$ Conversion factor, 32.174 lbm ft/lbf sec$^2$

$h$ Height (maximum) of a cross-section of a duct in the plane defined by radius r normal to the bend axis (h can be the same as a or b of a rectangular or elliptical duct for example), in.

$D$ Hydraulic diameter of a cross-section area of a duct, in.

$k$ Total pressure loss coefficient based on q

$k^+$ Total pressure loss coefficient based on (P - p)

$k^*$ Total pressure loss coefficient for the reference restriction (usually in the incompressible flow regime)

$\ell$ Length along the centerline of a duct, in.

$m$ Subscript slope of an orifice performance

$\dot{m}$ Mass flowrate, lbm/sec

$\dot{m}_{id}$ Ideal m which would pass through a lossless restriction if the avialable cross-sectional area flowed full, lbm/sec

$M$ Mach number

$n$ Supercritical constant for orifice performance

$p$ Static pressure of the air, psia

$P$ Total pressure of the air, psia

$(P - p)$ Impact pressure of the air, psia

$\mathbb{P}$ Perimeter of a duct cross-sectional area, in.

$q$ Dynamic pressure of the air, psi

$\mathbb{q}$ Volumetric or mass flow ratio, $Q_n/Q_3$ or $m_n/m_3$

$Q$ Volume flowrate, ft$^3$/sec

$r$ Radius of curvature for the centerline of a ciruclar-arc benc, or edge break or fillet radii at tube-wall intersections, in.

| | |
|---|---|
| $\mathscr{r}$ | Orifice pressure ratio, $P_o/P_u$ |
| r | Radius of a circular cross-section, in. |
| $\mathbf{r}$ | Relative radius, r/ D |
| $\mathbf{r}$ | Elliptical pressure ratio function for orifices, $1-r^2$ |
| R | Specific gas constant of the air, lbf ft/lbm deg R |
| Re | Reynolds number |
| T | Total temperature of the air, deg R |
| V | Velocity of the air, ft/sec |
| $V_{id}$ | Velocity of an isentropie one-dimensional flow filling the same area, ft/sec |
| x | Cartesian coordinate or an arbitrary geometrical variable |
| y | Cartesian coordinate or an arbitrary geometrical variable |
| $\alpha$ | Turning loss term for bend k-factor equations |
| $\beta$ | Complementary bend angle, degrees |
| $\Upsilon$ | Ratio of specific heats of the air, $c_p/c_v$ |
| $\varepsilon$ | Effective "sand grain" wall roughness, in. |
| $\Theta$ | Bend angle, degrees |
| $\lambda$ | Sudden expansion area ratio, $A_1/A_2$ |
| $\Lambda$ | Sudden contraction area ratio, $A_2/A_1$, or $A_1/A_o$ fpr profoces |
| $\mu$ | Dynamic viscosity of the air, lbm/ft sec |
| $\rho$ | Static density of the air, $lbm/ft^3$ |
| $\Phi$ | Compressible flow parameter, $m \sqrt{T}/P\ A$, lbm $°R^{1/2}$/lbf sec |
| $\Phi$ | Elliptical flow parameter function for orifices, $\Phi^2$ |

NOMENCLATURE (con't)

Superscripts

| | |
|---|---|
| $\bar{}$ | Average or effective value of a nonconstant parameter |
| * | Critical condition, M = 1.0 |

Subscripts

| | |
|---|---|
| b | Bend restriction |
| c | Fluid stream contraction due to separation at an abrupt flow area reduction, primarily a vena contracta |
| d | Downstream tangent duct |
| D | Downstream of a restriction |
| e | Restriction exit area component (discharge contribution) |
| i | Inside wall |
| n | General location in the internal flow system |
| o | Outside wall |
| sc | Sudden contraction restriction |
| se | Sudden expansion restriction |
| u | Upstream tangent duct |
| U | Upstream of a restriction |
| v | Velocity of the fluid stream |
| 0 | Free stream condition upstream of a flow obstacle |
| 1 | Inlet aea of a flow restriction |
| 2 | Exit area of a flow restriction |
| 3 | Junction or branch leg carrying the combined flow |

## APPENDIX

### Summary of Derivations

This Appendix contains the detailed calculations for:

Restriction 1--Orifice flow characteristics for a nozzle-like geometry. The Dodge (24) model was used to obtain k-factors for the DU1 program.

Restriction 2--Orifice flow characteristics for a thin-plate geometry. The Perry (29) model was used to develop the flow characteristic curve. The Dodge (24) model was used to obtain k-factors for the DU1 program.

The flow characteristic curve was converted to an overall k-factor curve (KURVE2) suitable for internal DU1 use, as demonstrated by the Restriction 7 calculation.

Restriction 3--The Dodge model was used to generate an orifice flow characteristic representative of the minimum component losses of Table VI. An "incompressible" flow slope of $m = 0.317$ was found at $r \sim 0.87$. This yields a value of $a = 0.544$ which exceeds the theoretical limit of $a = 0.532$ for air. Therefore, the need to observe the overall slope limit, $m < 0.26$, in addition to the component loss limits is demonstrated.

Restriction 4--Provides a comparison of the static orifice curve calculated by the Dodge model with the test data correlation of Perry (29). The need for an alternative model for highly separated orifices can be seen from the flow characteristic discrepance at high $P_U/P_D$.

Restriction 5--Demonstrates the use of a k-factor curve for the accurate representation of orifice performance in a DU1 restriction calculation. The CURVE1 example is for the static orifice of Perry (29).

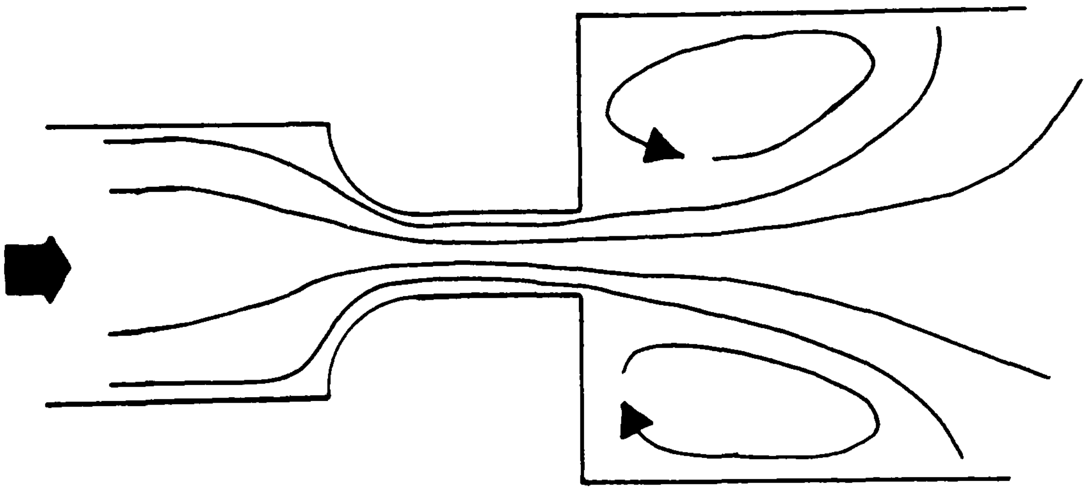
Restriction 6--Demonstrates the rapid expansion of the vena contracta in high-speed compressible flow. It can be seen that $\ell/D = 1.2$ is the theoretical limit for a Perry model of a static orifice.

Restriction 7--Verifies the equivalence of the k-factor curve (KURVE2) to the DU1 flow characteristic calculated for Restriction 2.

Restriction 8 (2k)--Demonstrates an imbedded k-factor curve (KURVE2) for a standard component within a more estensive flow characteristic model, W$\sqrt{T_U}/P_U$ versus $P_U/P_D$, ($A_n$ = constant, as modeled).

Restriction 8 (A*)--Demonstrates the generalization of an extensive flow characteristic model (in this case, restriction 8(2K)) to all geometrically similar restrictions on the arbitrary basis of the minimum flow area, $A_0$ (KURVE2).

Restriction 1: Generalized Thick-Wall Orifice Model



Given

$A_0/A_1$ = 6.0 sudden contraction

$r/D$ = 0.2 rounded edge

$\ell/D$ = 1.2 orifice thickness

$\varepsilon/D$ $1(10^{-4})$ wall roughness

$A_2/A_1$ = 30. Sudden expansion

Find compressible flow characteristic $\gamma = 1.4$ and $R = 53.342$ lbb ft/lbm °R

Dodge (24) incompressible flow model

$$K_\theta = k_{sc} + K_\ell + k_f + K_{se}$$

$k_{sc}^* = 0.5$

$C_r = 0.06$ Fig 21 $r/D = 0.2$

$K_\ell^* = 0.43$ Fig 23 $\ell/D = 1.2$

4f Moody correlation $D = 0.35$ in.
$\ell = 0.42$ in.
$\epsilon = 30\ \mu$ in.

$\Lambda = A_1/A_o = 0.167$ $\beta_1 = 0.408$

$\lambda = A_1/A_2 = 0.033$ $\beta_2 = 0.183$

Sudden contraction

$$k_{sc} = C_r\ k^*_{sc}[1 - \Lambda]$$

$$= (0.06)\ 0.5\ [0.833]$$

$$= 0.025 \qquad (\ll 0.4)$$

Vena contracta

$$k = C_r^{1/2} k^*_{\ell}\ [1 - \Lambda]^{1/2}\ ]1 - \lambda]$$

$$= (0.245)\ 0.43\ ]0.913]\ [0.967]$$

$$= 0.093 \qquad (\ll 0.65)$$

Wall friction

$k_f = 4f\ (\ell/\ D)$ Internal calculation

Sudden expansion

$$k_{se} = [1 - \lambda]^2 \qquad (\lambda < 0.125)$$

$$= 0.934$$

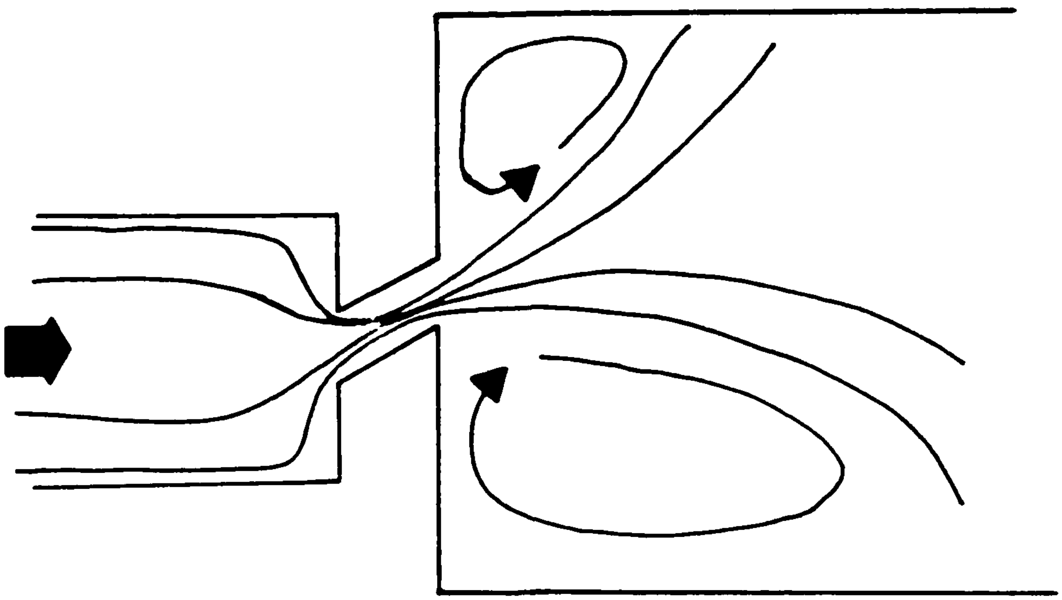
Slope

$m = \Phi/r$ near $P_u/P_D \leq 1.15$

| | | |
|---|---|---|
| $P_u/P_D$ | 1.1283607 | 1.1761978 |
| $\Phi$ | 0.3351456 | 0.3757693 |
| $\Phi$ | 0.11232 | 0.14120 |
| | 0.21458 | 0.27195 |
| m | 0.52346 | 0.51922 |
| n | 0.37128 | 0.36977 |
| a | 0.69829 | 0.69545 |
| r* | 0.52828 | 0.52828 |
| $\Phi$* | 0.61431 | 0.61181 |

| | | |
|---|---|---|
| $P_u/P_D$ | 1.1177461 | 1.1710073 |
| $\phi$ | 0.2323073 | 0.2689874 |
| $\Phi$ | 0.05397 | 0.07235 |
| | 0.19959 | 0.27074 |
| m | 0.27039 slightly exceeds $m_{max}$ | 0.26724 |
| n | 0.26684 | 0.26528 |
| a | 0.50187 | 0.49894 |
| r* | 0.52828 | 0.52828 |
| $\phi$* | 0.44151 | 0.43893 |

Restriction 2--Generalized Thin Wall Orifice Model



Given

$A_0/A_1$ = 6.0 Sudden contraction

θ = 45° edge break, $\ell_{sc}/D$ = 0.02 (α = 90°_

θ = 30° hole angularity end wall approaching flow

$\ell/D$ = 0.5 orifice thickness

$\epsilon/D$ $1(10^{-4})$ wall roughness

$A_2/A_1$ = 10. Sudden expansion

Find

compressible flow characteristic for γ = 1.4 and R = 53.342 lbf ft/lbm °R

Dodge (24) incompressible flow model

$k_{\theta} = k_{sc} + k_{\ell} + k_f + k_{se}$

$k^*_{sc} = 0.5$

$C_r = 0.85$ Fig. 21 $\ell_{sc}/D = 0.02$, $\alpha = 90°$

$C_{\alpha} = 1.35$ Fig. 20 $\theta = 30°$ Weisbach Eq.

$k^*_{\ell} = 1.00$ Fig. 23 $\ell/D = 0.5$

4f Moody correlation
$D = 0.35$ in.
$\ell$ 0.18 in.
$\epsilon = 30\ \mu$ in.

$\Lambda = A_1/A_0 = 0.167$ $\beta_1 = 0.408$

$\lambda = A_1/A_2 = 0.100$ $\beta_2 = 0.316$

Sudden contraction

$$k_{sc} = C_{\alpha}\, C_r\, k^*_{sc}\ ]1 - \Lambda]$$

$$= 1.35\ (0.85)\ 0.5\ ]0.833]$$

$$= 0.478 \qquad (> 0.4)$$

Vena contracta

$$k_{\ell} = (C_{\alpha}\, C_r)^{1/2}\, k^*_{sc}[1 - \Lambda]^{1/2}\, [1 - \lambda]$$

$$= (1.071)\ 1.00\ [0.913]\ [0.900]$$

$$= 0.880 \qquad (< 0.65)$$

Wall friction

$k_f = 4f\ (\ell/D)$ Internal calculation

Sudden expansion

$k_{se} = [1 - \lambda]^2$ $(\lambda < 0.125)$

Slope

$m = \Phi/$ near $P_U/P_D \leq 1.15$

RES2—SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW - L/D = 0.5, EDGE-BREAK PERRY MODEL BASED ON DODGE "INCOMPRESSIBLE" PERFORMANCE FOR AIR

m = 0.2674 n = 0.2654 a = 0.4991

| $P_u/P_D$ | $r$ | $\phi$ | $M_\theta$ | $q/P$ | $k\theta$ |
|---|---|---|---|---|---|
| 1.00 | 1.0000 | 0 | 0 | 0 | 2.255 |
| 1.00363 | 0.99638 | 0.4394 | 0.4788 | 0.00160 | 2.25726 |
| 1.01780 | 0.98251 | 0.09629 | 0.10549 | 0.00773 | 2.26281 |
| 1.04161 | 0.96005 | 0.14470 | 0.15989 | 0.01758 | 2.27240 |
| 1.07493 | 0.93029 | 0.18968 | 0.21203 | 0.03050 | 2.28549 |
| 1.11775 | 0.89465 | 0.23102 | 0.26189 | 0.04577 | 2.30139 |
| 1.23561 | 0.80932 | 0.30373 | 0.35636 | 0.08142 | 2.34192 |
| 1.31332 | 0.76143 | 0.33521 | 0.40115 | 0.10082 | 2.34192 |
| 1.40726 | 0.71060 | 0.36383 | 0.44482 | 0.12091 | 2.39348 |
| 1.52107 | 0.65743 | 0.38965 | 0.48738 | 0.14134 | 2.42366 |
| 1.66159 | 0.60183 | 0.41297 | 0.52924 | 0.16201 | 2.45762 |
| 1.86193 | 0.53708 | 0.43620 | 0.57534 | 0.18514 | 2.50037 |
| 1.89293 | 0.52828 | 0.43906 | 0.58140 | 0.18820 | 2.50654 |
| 2.11115 | 0.47368 | 0.45326 | 0.61304 | 0.20413 | 2.57833 |
| 2.3 | 0.43478 | 0.46195 | 0.63391 | 0.21461 | 2.62267 |
| 2.5 | 0.40000 | 0.46881 | 0.65138 | 0.22334 | 2.68652 |
| 3.0 | 0.33333 | 0.47972 | 0.68140 | 0.23819 | 2.79890 |
| 3.5 | 0.28571 | 0.48588 | 0.69985 | 0.24720 | 2.88946 |
| 4.0 | 0.25000 | 0.48967 | 0.71187 | 0.25302 | 2.96419 |
| 5.0 | 0.20000 | 0.49386 | 0.72585 | 0.25972 | 3.08019 |
| 7.0 | 0.14286 | 0.49716 | 0.73746 | 0.26523 | 3.23165 |
| 10.0 | 0.10000 | 0.49865 | 0.74289 | 0.26780 | 3.36077 |
| 20.0 | 0.05000 | 0.49938 | 0.74560 | 0.26907 | 3.35070 |
| 100.0 | 0.01000 | 0.49922 | 0.74501 | 0.26879 | 3.68319 |
| 1000.0 | 0.00010 | 0.49908 | 0.74449 | 0.26854 | 3.72341 |

```
//////////////////// INPUT DATASET ////////////// D D A //////////

KURVE    1   20
 0.0       0.0328    0.0653    0.0925    0.1302    0.1586    0.1823
 0.2027    0.2460    0.2790    0.3080    0.3320    0.3540    0.3730
 0.3890    0.4030    0.4230    0.4360    0.4440    0.4490
 2.7940000 2.7940068 2.7940844 2.8042504 2.8195665 2.8322270 2.8460312
 2.8611360 2.8760168 2.9434909 2.9794882 3.0389848 3.0776563 3.1275657
 3.1960778 3.2702482 3.4953703 3.7851911 4.1324977 4.7688857
KURVE    2   20
 0.0       0.04394   0.09629   0.14470   0.18968   0.23102   0.26907
 0.30373   0.33521   0.36383   0.38965   0.41297   0.43906   0.45326
 0.46195   0.46881   0.47972   L.48588   0.49386   0.49908
 2.25500   2.25726   2.26281   2.27240   2.28549   2.30139   2.32019
 2.34192   2.36623   2.39348   2.42366   2.45762   2.50654   2.57833
 2.63367   2.68652   2.79890   2.88946   3.08019   3.72341
         1
 RES  1   SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW  24APR86
          BASED ON THE DODGE MODEL - L/D = 1.2, LEADING EDGE RADIUS
 5        0.10      1.40 28.97                                     PLOT
 0.60     540.
 0.10     540.      0.025                        Q
 0.10     540.      0.093                        Q
 0.10     540.                                         0.42 0.35 30.
 3.00     540.      0.934                       PT
          125.
         2
 RES  2   SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW  24APR86
          BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE
 5        0.10      1.40 28.97                                     PLOT
 0.60     540.
 0.10     540.      0.478                        Q
 0.10     540.      0.880                        Q
 0.10     540.                                         0.18 0.35 30.
 1.00     540.      0.810                       PT
          125.
         3
 RES  3   SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE  GFH 24APR86
          LIMIT OF THE DODGE MODEL   --   TABLE VI  COMPONENT LOSSES
 5        1.0       1.40 28.97                                     PLOT
1000.     100.
 1.00     100.      0.40                         Q
 1.00     100.      0.65                         Q
 1.00     100.                0.0
1000.     100.      0.766                       PT
          10.0
         4
 RES  4   SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE  GFH 24APR86
          BASED ON PERRY EMPIRICAL DATA AND DODGE INCOMPRESSIBLE MODEL
 5        1.0       1.40 28.97                                     PLOT
1000.     100.
 1.00     100.      0.50                         Q
 1.00     100.      1.34                         Q
 1.00     100.                0.0
1000.     100.      1.0                         PT
          10.0
         5
 RES  5   STATIC ORIFICE RESTRICTION IN COMPRESSIBLE FLOW  GFH  24APR86
          BASED ON THE K-FACTOR DATA TABLE FOR EMPIRICAL PERRY MODEL
 4        1.0       1.40 28.97                                     PLOT
10.000    100.
1.0000    100.
1.0000    100.                              1    Q
10.000    100.
          10.
         6
 RES  6   SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE  GFH 24APR86
          LIMIT OF THE DODGE MODEL   --   L/D = 1.2
 5        1.0       1.40 28.97                                     PLOT
1000.     100.
 1.00     100.      0.50                         Q
 1.00     100.      0.43                         Q
 1.00     100.                0.024
```

```
1000.      100.       1.0                             PT
           10.0
            7
 RES 7(2K)SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW  24APR86
          BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE
 4         0.10       1.40 28.97                                      PLOT
0.60       540.
0.10       540.
0.10       540.                                2    Q
1.00       540.
           125.
            8
 RES 8(2K)COMPLEX RESTRICTION MODEL INCLUDING GENERALIZED ORIFICE RES 2
          BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE
 8         1.00       1.40 28.97                                      PLOT
1000.      600.
1.00       600.       0.578                             Q
1.00       580.                                                5.50 1.12850.
0.60       540.       0.050                             Q
0.10       540.                                2    Q
1.00       540.
1.00       520.                                                3.00 1.12850.
1000.      500.       1.0                             PT
           125.
            9
 RES 8(A*)COMPLEX RESTRICTION MODEL INCLUDING GENERALIZED ORIFICE RES 2
          BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE
 8         0.10       1.40 28.97                                      PLOT
1000.      600.
1.00       600.       0.578                             Q
1.00       580.                                                5.50 1.12850.
0.60       540.       0.050                             Q
0.10       540.                                2    Q
1.00       540.
1.00       520.                                                3.00 1.12850.
1000.      500.       1.0                             PT
           125.
```

CURVE NUMBER 1

RES 1 SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW 24APR86
BASED ON THE DODGE MODEL - L/D = 1.2, LEADING EDGE RADIUS

NUMBER OF ITERATIONS = 23

W= 0.27315 LBS/SEC GAMMA= 1.40 MW=28.97 LB/LB-MOL

| STN | AREA | TT(I) | WRT/PTA | WRT/PSA | 4FL/D | KFACT | KURVE | PT | PS | MN | KFACT METH | PIN ROWS | LENGTH | HD | ROUGH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.60000 | 540.00 | 0.0846 | 0.0851 | 0.0 | 0.0 | 0 | 125.000 | 124.253 | 0.093 | | 0 | 0.0 | 0.0 | 0.0 |
| 2 | 0.10000 | 540.00 | 0.5114 | 0.7767 | 0.0 | 0.025 | 0 | 124.110 | 81.723 | 0.796 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 3 | 0.10000 | 540.00 | 0.5257 | 0.8762 | 0.0 | 0.093 | 0 | 120.737 | 72.442 | 0.886 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 4 | 0.10000 | 540.00 | 0.5318 | 1.0063 | 0.019 | 0.0 | 0 | 119.859 | 63.074 | 1.000 | | 0 | 0.4200 | 0.3500 | 30.0 |
| 5 | 3.00000 | 540.00 | 0.0317 | 0.0317 | 0.0 | 0.934 | 0 | 66.789 | 66.734 | 0.034 | PT-PS | 0 | 0.0 | 0.0 | 0.0 |

* OVERALL CONDITIONS *

| PTIN/PTEX | PTIN/PSEX | WRTIN/PTIN | WRTIN/PSIN | PTI-PTE/PTI | PTI-PSE/PTI |
|---|---|---|---|---|---|
| 1.8716 | 1.8731 | 0.05078 | 0.05108 | 0.4657 | 0.4661 |

END OF CHOKE POINT CALCULATION

FLOW CURVE CALCULATED BY DU1

| CURVE | POINTS | AREF |
|---|---|---|
| 1 | 14 | .100000 |

RES 1 SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW 24APR86

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PR | 1.00000 | 1.00281 | 1.01361 | 1.03174 | 1.05681 | 1.08895 | 1.12836 | 1.17620 | 1.23344 | 1.30201 | 1.38597 | 1.49301 | 1.64968 | 1.87156 |
| PHI | 0.0 | 0.05586 | 0.12187 | 0.18281 | 0.23866 | 0.28944 | 0.33515 | 0.37577 | 0.41132 | 0.44178 | 0.46717 | 0.48748 | 0.50272 | 0.50780 |

CURVE NUMBER 2

RES 2 SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW 24APR86
BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE

NUMBER OF ITERATIONS = 24

W= 0.21923 LBS/SEC GAMMA= 1.40 MW=28.97 LB/LB-MOL

| STN | AREA | TT(I) | WRT/PTA | WRT/PSA | 4FL/D | KFACT | KURVE | PT | PS | MN | KFACT METH | PIN ROWS | LENGTH | HD | ROUGH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.60000 | 540.00 | 0.0679 | 0.0682 | 0.0 | 0.0 | 0 | 125.000 | 124.520 | 0.074 | | 0 | 0.0 | 0.0 | 0.0 |
| 2 | 0.10000 | 540.00 | 0.4406 | 0.5554 | 0.0 | 0.478 | 0 | 115.619 | 91.724 | 0.585 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 3 | 0.10000 | 540.00 | 0.5290 | 0.9170 | 0.0 | 0.880 | 0 | 96.300 | 55.554 | 0.922 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 4 | 0.10000 | 540.00 | 0.5318 | 1.0063 | 0.008 | 0.0 | 0 | 95.797 | 50.627 | 1.000 | | 0 | 0.1800 | 0.3500 | 30.0 |
| 5 | 1.00000 | 540.00 | 0.0860 | 0.0866 | 0.0 | 0.810 | 0 | 59.210 | 58.844 | 0.094 | PT-PS | 0 | 0.0 | 0.0 | 0.0 |

* OVERALL CONDITIONS *

| PTIN/PTEX | PTIN/PSEX | WRTIN/PTIN | WRTIN/PSIN | PTI-PTE/PTI | PTI-PSE/PTI |
|---|---|---|---|---|---|
| 2.1111 | 2.1243 | 0.04076 | 0.04091 | 0.5263 | 0.5292 |

END OF CHOKE POINT CALCULATION

FLOW CURVE CALCULATED BY DU1

| CURVE | POINTS | AREF |
|---|---|---|
| 2 | 14 | .100000 |

RES 2 SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW 24APR86

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PR | 1.00000 | 1.00363 | 1.01780 | 1.04161 | 1.07493 | 1.11775 | 1.17101 | 1.23561 | 1.31332 | 1.40726 | 1.52107 | 1.66159 | 1.86193 | 2.11115 |
| PHI | 0.0 | 0.04483 | 0.09781 | 0.14672 | 0.19155 | 0.23231 | 0.26899 | 0.30159 | 0.33012 | 0.35457 | 0.37495 | 0.39125 | 0.40348 | 0.40756 |

CURVE NUMBER 3

RES 3 SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE GFH 24APR86
LIMIT OF THE DODGE MODEL -- TABLE VI COMPONENT LOSSES

NUMBER OF ITERATIONS = 23

W= 0.42672 LBS/SEC GAMMA= 1.40 MW=28.97 LB/LB-MOL

| STN | AREA | TT(I) | WRT/PTA | WRT/PSA | 4FL/D | KFACT | KURVE | PT | PS | MN | KFACT METH | PIN ROWS | LENGTH | HD | ROUGH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1000.00000 | 100.00 | 0.0004 | 0.0004 | 0.0 | 0.0 | 0 | 10.000 | 10.000 | 0.000 | | 0 | 0.0 | 0.0 | 0.0 |
| 2 | 1.00000 | 100.00 | 0.4589 | 0.5978 | 0.0 | 0.400 | 0 | 9.299 | 7.138 | 0.626 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 3 | 1.00000 | 100.00 | 0.5318 | 1.0062 | 0.0 | 0.650 | 0 | 8.024 | 4.241 | 1.000 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 4 | 1.00000 | 100.00 | 0.5318 | 1.0062 | 0.0 | 0.0 | 0 | 8.024 | 4.241 | 1.000 | | 0 | 0.0 | 0.0 | 0.0 |
| 5 | 1000.00000 | 100.00 | 0.0008 | 0.0008 | 0.0 | 0.766 | 0 | 5.126 | 5.126 | 0.001 | PT-PS | 0 | 0.0 | 0.0 | 0.0 |

* OVERALL CONDITIONS *

| PTIN/PTEX | PTIN/PSEX | WRTIN/PTIN | WRTIN/PSIN | PTI-PTE/PTI | PTI-PSE/PTI |
|---|---|---|---|---|---|
| 1.9508 | 1.9508 | 0.42672 | 0.42672 | 0.4874 | 0.4874 |

END OF CHOKE POINT CALCULATION

FLOW CURVE CALCULATED BY DU1

| CURVE | POINTS | AREF |
|---|---|---|
| 3 | 14 | 1.00000 |

RES 3 SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE GFH 24APR86

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PR | 1.00000 | 1.00334 | 1.01625 | 1.03793 | 1.06816 | 1.10679 | 1.15467 | 1.21229 | 1.28097 | 1.36284 | 1.46135 | 1.58299 | 1.74921 | 1.95078 |
| PHI | 0.0 | 0.04694 | 0.10241 | 0.15362 | 0.20056 | 0.24323 | 0.28168 | 0.31577 | 0.34564 | 0.37124 | 0.39258 | 0.40965 | 0.42245 | 0.42672 |

CURVE NUMBER 4

RES 4 SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE GFH 24APR86
BASED ON PERRY EMPIRICAL DATA AND DODGE INCOMPRESSIBLE MODEL

NUMBER OF ITERATIONS = 24

W= 0.38625 LBS/SEC GAMMA= 1.40 MW=28.97 LB/LB-MOL

| STN | AREA | TT(I) | WRT/PTA | WRT/PSA | 4FL/D | KFACT | KURVE | PT | PS | MN | KFACT METH | PIN ROWS | LENGTH | HD | ROUGH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1000.00000 | 100.00 | 0.0004 | 0.0004 | 0.0 | 0.0 | 0 | 10.000 | 10.000 | 0.000 | | 0 | 0.0 | 0.0 | 0.0 |
| 2 | 1.00000 | 100.00 | 0.4150 | 0.5036 | 0.0 | 0.500 | 0 | 9.307 | 7.670 | 0.533 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 3 | 1.00000 | 100.00 | 0.5318 | 1.0061 | 0.0 | 1.340 | 0 | 7.263 | 3.839 | 1.000 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 4 | 1.00000 | 100.00 | 0.5318 | 1.0061 | 0.0 | 0.0 | 0 | 7.263 | 3.839 | 1.000 | | 0 | 0.0 | 0.0 | 0.0 |
| 5 | 1000.00000 | 100.00 | 0.0010 | 0.0010 | 0.0 | 1.000 | 0 | 3.839 | 3.839 | 0.001 | PT-PS | 0 | 0.0 | 0.0 | 0.0 |

* OVERALL CONDITIONS *

| PTIN/PTEX | PTIN/PSEX | WRTIN/PTIN | WRTIN/PSIN | PTI-PTE/PTI | PTI-PSE/PTI |
|---|---|---|---|---|---|
| 2.6048 | 2.6048 | 0.38625 | 0.38625 | 0.6161 | 0.6161 |

END OF CHOKE POINT CALCULATION

FLOW CURVE CALCULATED BY DU1

| CURVE | POINTS | AREF |
|---|---|---|
| 4 | 14 | 1.00000 |

RES 4 SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE GFH 24APR86

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PR | 1.00000 | 1.00428 | 1.02091 | 1.04910 | 1.08892 | 1.14079 | 1.20619 | 1.28756 | 1.38777 | 1.51227 | 1.66706 | 1.87249 | 2.18351 | 2.60475 |
| PHI | 0.0 | 0.04249 | 0.09270 | 0.13905 | 0.18154 | 0.22016 | 0.25493 | 0.28583 | 0.31286 | 0.33604 | 0.35535 | 0.37080 | 0.38239 | 0.38625 |

CURVE NUMBER 5

RES 5 STATIC ORIFICE RESTRICTION IN COMPRESSIBLE FLOW GFH 24APR86
BASED ON THE K-FACTOR DATA TABLE FOR EMPIRICAL PERRY MODEL

NUMBER OF ITERATIONS = 24

W= 0.35036 LBS/SEC GAMMA= 1.40 MW=28.97 LB/LB-MOL

| STN | AREA | TT(I) | WRT/PTA | WRT/PSA | 4FL/D | KFACT | KURVE | PT | PS | MN | KFACT METH | PIN ROWS | LENGTH | HD | ROUGH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 10.00000 | 100.00 | 0.0350 | 0.0351 | 0.0 | 0.0 | 0 | 10.000 | 9.990 | 0.038 | | 0 | 0.0 | 0.0 | 0.0 |
| 2 | 1.00000 | 100.00 | 0.3504 | 0.3964 | 0.0 | 0.0 | 0 | 10.000 | 8.838 | 0.424 | | 0 | 0.0 | 0.0 | 0.0 |
| 3 | 1.00000 | 100.00 | 0.5318 | 1.0060 | 0.0 | 3.070 | 1 | 6.588 | 3.482 | 0.999 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 4 | 10.00000 | 100.00 | 0.0532 | 0.0533 | 0.0 | 0.0 | 0 | 6.588 | 6.573 | 0.058 | | 0 | 0.0 | 0.0 | 0.0 |

* OVERALL CONDITIONS *

| PTIN/PTEX | PTIN/PSEX | WRTIN/PTIN | WRTIN/PSIN | PTI-PTE/PTI | PTI-PSE/PTI |
|---|---|---|---|---|---|
| 1.5179 | 1.5214 | 0.35036 | 0.35071 | 0.3412 | 0.3427 |

END OF CHOKE POINT CALCULATION

FLOW CURVE CALCULATED BY DU1

| CURVE | POINTS | AREF |
|---|---|---|
| 5 | 14 | 1.00000 |

RES 5 STATIC ORIFICE RESTRICTION IN COMPRESSIBLE FLOW GFH 24APR86

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PR | 1.00000 | 1.00345 | 1.01676 | 1.03895 | 1.06929 | 1.10728 | 1.15093 | 1.20330 | 1.26181 | 1.32239 | 1.38688 | 1.44669 | 1.49744 | 1.51787 |
| PHI | 0.0 | 0.03854 | 0.08409 | 0.12613 | 0.16467 | 0.19970 | 0.23124 | 0.25926 | 0.28379 | 0.30481 | 0.32233 | 0.33634 | 0.34685 | 0.35036 |

CURVE NUMBER 6

RES 6 SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE GFH 24APR86
LIMIT OF THE DODGE MODEL -- L/D = 1.2
FOR STATION 4 TEMP SHOULD NOT BE 100. FOR FRICTION CALC
FOR STATION 1 PRESSURE SHOULD NOT BE 10. FOR FRICTION CALC

NUMBER OF ITERATIONS = 23

W= 0.43047 LBS/SEC GAMMA= 1.40 MW=28.97 LB/LB-MOL

| STN | AREA | TT(I) | WRT/PTA | WRT/PSA | 4FL/D | KFACT | KURVE | PT | PS | MN | KFACT METH | PIN ROWS | LENGTH | HD | ROUGH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1000.00000 | 100.00 | 0.0004 | 0.0004 | 0.0 | 0.0 | 0 | 10.000 | 10.000 | 0.000 | | 0 | 0.0 | 0.0 | 0.0 |
| 2 | 1.00000 | 100.00 | 0.4728 | 0.6345 | 0.0 | 0.500 | 0 | 9.104 | 6.784 | 0.662 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 3 | 1.00000 | 100.00 | 0.5244 | 0.8632 | 0.0 | 0.430 | 0 | 8.209 | 4.987 | 0.875 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 4 | 1.00000 | 100.00 | 0.5318 | 1.0058 | 0.024 | 0.0 | 0 | 8.095 | 4.280 | 0.999 | | 0 | 0.0 | 0.0 | 0.0 |
| FOR STATION 4 TEMP SHOULD NOT BE 100. FOR FRICTION CALC | | | | | | | | | | | | | | | |
| 5 | 1000.00000 | 100.00 | 0.0010 | 0.0010 | 0.0 | 1.000 | 0 | 4.280 | 4.280 | 0.001 | PT-PS | 0 | 0.0 | 0.0 | 0.0 |

* OVERALL CONDITIONS *

| PTIN/PTEX | PTIN/PSEX | WRTIN/PTIN | WRTIN/PSIN | PTI-PTE/PTI | PTI-PSE/PTI |
|---|---|---|---|---|---|
| 2.3366 | 2.3366 | 0.43047 | 0.43047 | 0.5720 | 0.5720 |

END OF CHOKE POINT CALCULATION

FLOW CURVE CALCULATED BY DU1

| CURVE | POINTS | AREF |
|---|---|---|
| 6 | 14 | 1.00000 |

RES 6 SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE GFH 24APR86

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PR | 1.00000 | 1.00361 | 1.01787 | 1.04180 | 1.07541 | 1.11888 | 1.17356 | 1.24066 | 1.32274 | 1.42379 | 1.55034 | 1.71625 | 1.96955 | 2.33660 |
| PHI | 0.0 | 0.04735 | 0.10331 | 0.15497 | 0.20232 | 0.24537 | 0.28411 | 0.31855 | 0.34868 | 0.37451 | 0.39603 | 0.41325 | 0.42616 | 0.43047 |

CURVE NUMBER 7

RES 7(2K)SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW 24APR86
BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE

NUMBER OF ITERATIONS = 24

W= 0.19943 LBS/SEC GAMMA= 1.40 MW=28.97 LB/LB-MOL

| STN | AREA | TT(I) | WRT/PTA | WRT/PSA | 4FL/D | KFACT | KURVE | PT | PS | MN | KFACT METH | PIN ROWS | LENGTH | HD | ROUGH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.60000 | 540.00 | 0.0618 | 0.0620 | 0.0 | 0.0 | 0 | 125.000 | 124.603 | 0.067 | | 0 | 0.0 | 0.0 | 0.0 |
| 2 | 0.10000 | 540.00 | 0.3707 | 0.4275 | 0.0 | 0.0 | 0 | 125.000 | 108.395 | 0.456 | | 0 | 0.0 | 0.0 | 0.0 |
| 3 | 0.10000 | 540.00 | 0.5318 | 1.0063 | 0.0 | 2.401 | 2 | 87.144 | 46.052 | 1.000 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 4 | 1.00000 | 540.00 | 0.0532 | 0.0533 | 0.0 | 0.0 | 0 | 87.144 | 86.939 | 0.058 | | 0 | 0.0 | 0.0 | 0.0 |

* OVERALL CONDITIONS *

| PTIN/PTEX | PTIN/PSEX | WRTIN/PTIN | WRTIN/PSIN | PTI-PTE/PTI | PTI-PSE/PTI |
|---|---|---|---|---|---|
| 1.4344 | 1.4378 | 0.03707 | 0.03719 | 0.3029 | 0.3045 |

END OF CHOKE POINT CALCULATION

FLOW CURVE CALCULATED BY DU1

| CURVE | POINTS | AREF |
|---|---|---|
| 7 | 14 | .100000 |

RES 7(2K)SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW 24APR86

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PR | 1.00000 | 1.00312 | 1.01514 | 1.03504 | 1.06211 | 1.09562 | 1.13495 | 1.17965 | 1.22818 | 1.27896 | 1.32963 | 1.37810 | 1.41903 | 1.43442 |
| PHI | 0.0 | 0.04078 | 0.08898 | 0.13347 | 0.17425 | 0.21132 | 0.24469 | 0.27435 | 0.30030 | 0.32254 | 0.34108 | 0.35591 | 0.36703 | 0.37074 |

CURVE NUMBER 8

RES 8(2K)COMPLEX RESTRICTION MODEL INCLUDING GENERALIZED ORIFICE RES 2
BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE

NUMBER OF ITERATIONS = 24

W= 0.19922 LBS/SEC GAMMA= 1.40 MW=28.97 LB/LB-MOL

| STN | AREA | TT(I) | WRT/PTA | WRT/PSA | 4FL/D | KFACT | KURVE | PT | PS | MN | KFACT METH | PIN ROWS | LENGTH | HD | ROUGH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1000.00000 | 600.00 | 0.0000 | 0.0000 | 0.0 | 0.0 | 0 | 125.000 | 125.000 | 0.000 | | 0 | 0.0 | 0.0 | 0.0 |
| 2 | 1.00000 | 600.00 | 0.0391 | 0.0391 | 0.0 | 0.578 | 0 | 124.909 | 124.750 | 0.043 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 3 | 1.00000 | 580.00 | 0.0384 | 0.0385 | 0.080 | 0.0 | 0 | 124.894 | 124.736 | 0.043 | | 0 | 5.5000 | 1.1280 | 50.0 |
| 4 | 0.60000 | 540.00 | 0.0618 | 0.0620 | 0.0 | 0.050 | 0 | 124.873 | 124.477 | 0.067 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 5 | 0.10000 | 540.00 | 0.5318 | 1.0058 | 0.0 | 2.401 | 2 | 87.055 | 46.027 | 0.999 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 6 | 1.00000 | 540.00 | 0.0532 | 0.0533 | 0.0 | 0.0 | 0 | 87.055 | 86.851 | 0.058 | | 0 | 0.0 | 0.0 | 0.0 |
| 7 | 1.00000 | 520.00 | 0.0522 | 0.0523 | 0.043 | 0.0 | 0 | 87.046 | 86.841 | 0.058 | | 0 | 3.0000 | 1.1280 | 50.0 |
| 8 | 1000.00000 | 500.00 | 0.0001 | 0.0001 | 0.0 | 1.000 | 0 | 86.841 | 86.841 | 0.000 | PT-PS | 0 | 0.0 | 0.0 | 0.0 |

* OVERALL CONDITIONS *

| PTIN/PTEX | PTIN/PSEX | WRTIN/PTIN | WRTIN/PSIN | PTI-PTE/PTI | PTI-PSE/PTI |
|---|---|---|---|---|---|
| 1.4394 | 1.4394 | 0.03904 | 0.03904 | 0.3053 | 0.3053 |

END OF CHOKE POINT CALCULATION

FLOW CURVE CALCULATED BY DU1

| CURVE | POINTS | AREF |
|---|---|---|
| 8 | 14 | 1.00000 |

RES 8(2K)COMPLEX RESTRICTION MODEL INCLUDING GENERALIZED ORIFICE RES 2

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PR | 1.00000 | 1.00314 | 1.01523 | 1.03525 | 1.06251 | 1.09627 | 1.13592 | 1.18113 | 1.23030 | 1.28164 | 1.33300 | 1.38218 | 1.42377 | 1.43941 |
| PHI | 0.0 | 0.00429 | 0.00937 | 0.01405 | 0.01835 | 0.02225 | 0.02577 | 0.02889 | 0.03162 | 0.03396 | 0.03592 | 0.03748 | 0.03865 | 0.03904 |

CURVE NUMBER 9

RES 8(A*)COMPLEX RESTRICTION MODEL INCLUDING GENERALIZED ORIFICE RES 2
BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE

NUMBER OF ITERATIONS = 24

W= 0.19922 LBS/SEC GAMMA= 1.40 MW=28.97 LB/LB-MOL

| STN | AREA | TT(I) | WRT/PTA | WRT/PSA | 4FL/D | KFACT | KURVE | PT | PS | MN | KFACT METH | PIN ROWS | LENGTH | HD | ROUGH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1000.00000 | 600.00 | 0.0000 | 0.0000 | 0.0 | 0.0 | 0 | 125.000 | 125.000 | 0.000 | | 0 | 0.0 | 0.0 | 0.0 |
| 2 | 1.00000 | 600.00 | 0.0391 | 0.0391 | 0.0 | 0.578 | 0 | 124.909 | 124.750 | 0.043 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 3 | 1.00000 | 580.00 | 0.0384 | 0.0385 | 0.080 | 0.0 | 0 | 124.894 | 124.736 | 0.043 | | 0 | 5.5000 | 1.1280 | 50.0 |
| 4 | 0.60000 | 540.00 | 0.0618 | 0.0620 | 0.0 | 0.050 | 0 | 124.873 | 124.477 | 0.067 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 5 | 0.10000 | 540.00 | 0.5318 | 1.0058 | 0.0 | 2.401 | 2 | 87.055 | 46.027 | 0.999 | Q | 0 | 0.0 | 0.0 | 0.0 |
| 6 | 1.00000 | 540.00 | 0.0532 | 0.0533 | 0.0 | 0.0 | 0 | 87.055 | 86.851 | 0.058 | | 0 | 0.0 | 0.0 | 0.0 |
| 7 | 1.00000 | 520.00 | 0.0522 | 0.0523 | 0.043 | 0.0 | 0 | 87.046 | 86.841 | 0.058 | | 0 | 3.0000 | 1.1280 | 50.0 |
| 8 | 1000.00000 | 500.00 | 0.0001 | 0.0001 | 0.0 | 1.000 | 0 | 86.841 | 86.841 | 0.000 | PT-PS | 0 | 0.0 | 0.0 | 0.0 |

* OVERALL CONDITIONS *

| PTIN/PTEX | PTIN/PSEX | WRTIN/PTIN | WRTIN/PSIN | PTI-PTE/PTI | PTI-PSE/PTI |
|---|---|---|---|---|---|
| 1.4394 | 1.4394 | 0.03904 | 0.03904 | 0.3053 | 0.3053 |

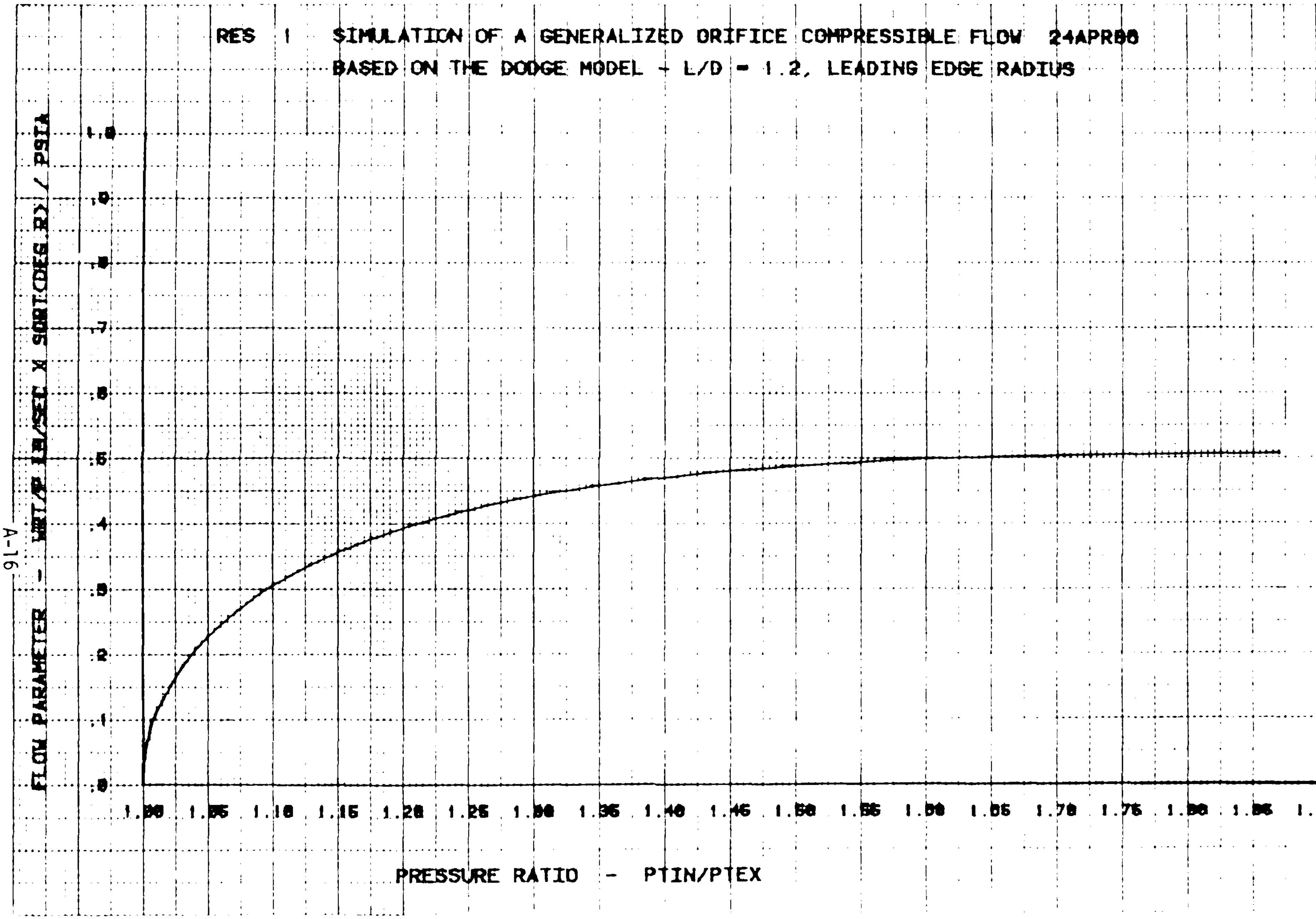
END OF CHOKE POINT CALCULATION

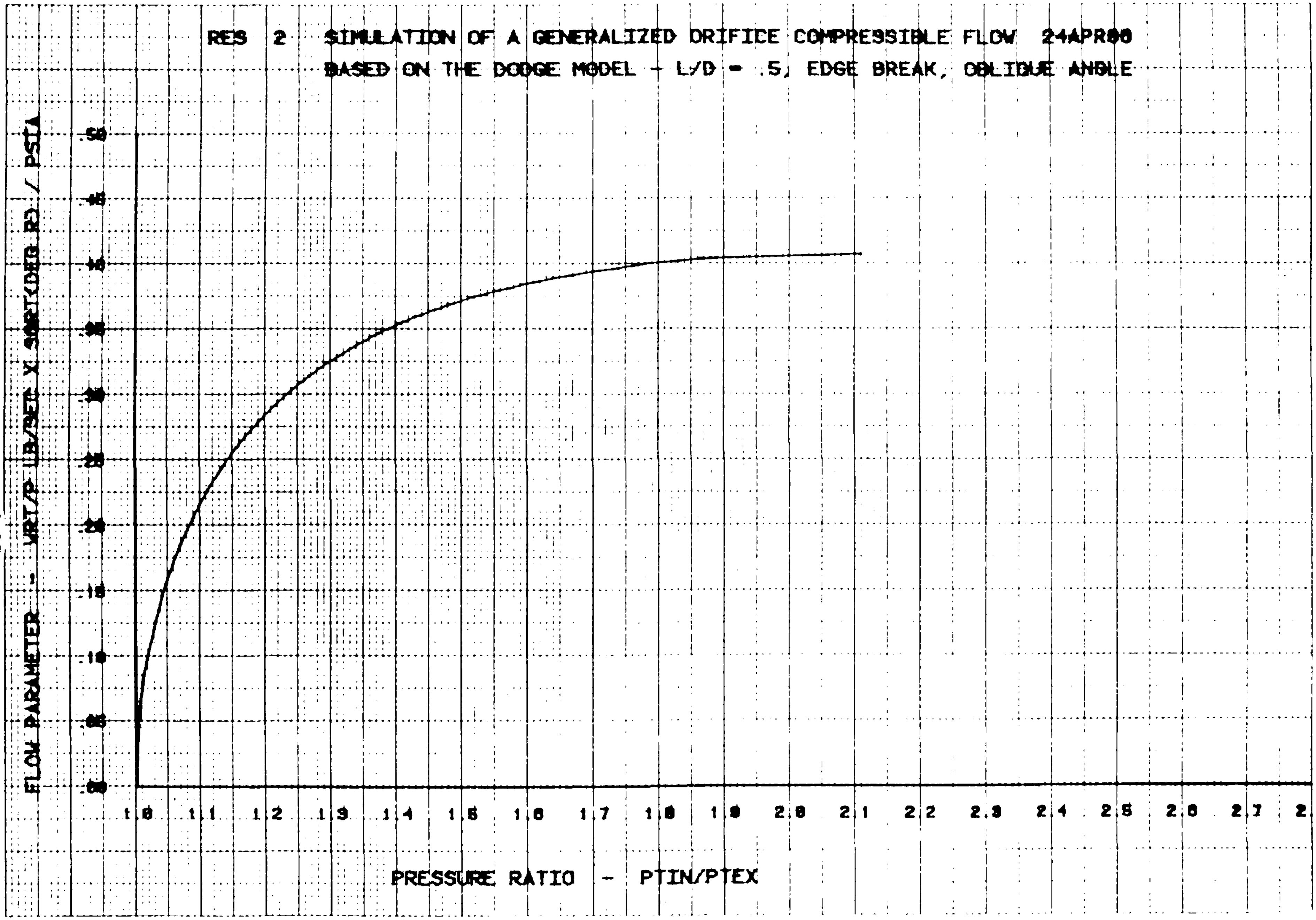
FLOW CURVE CALCULATED BY DU1

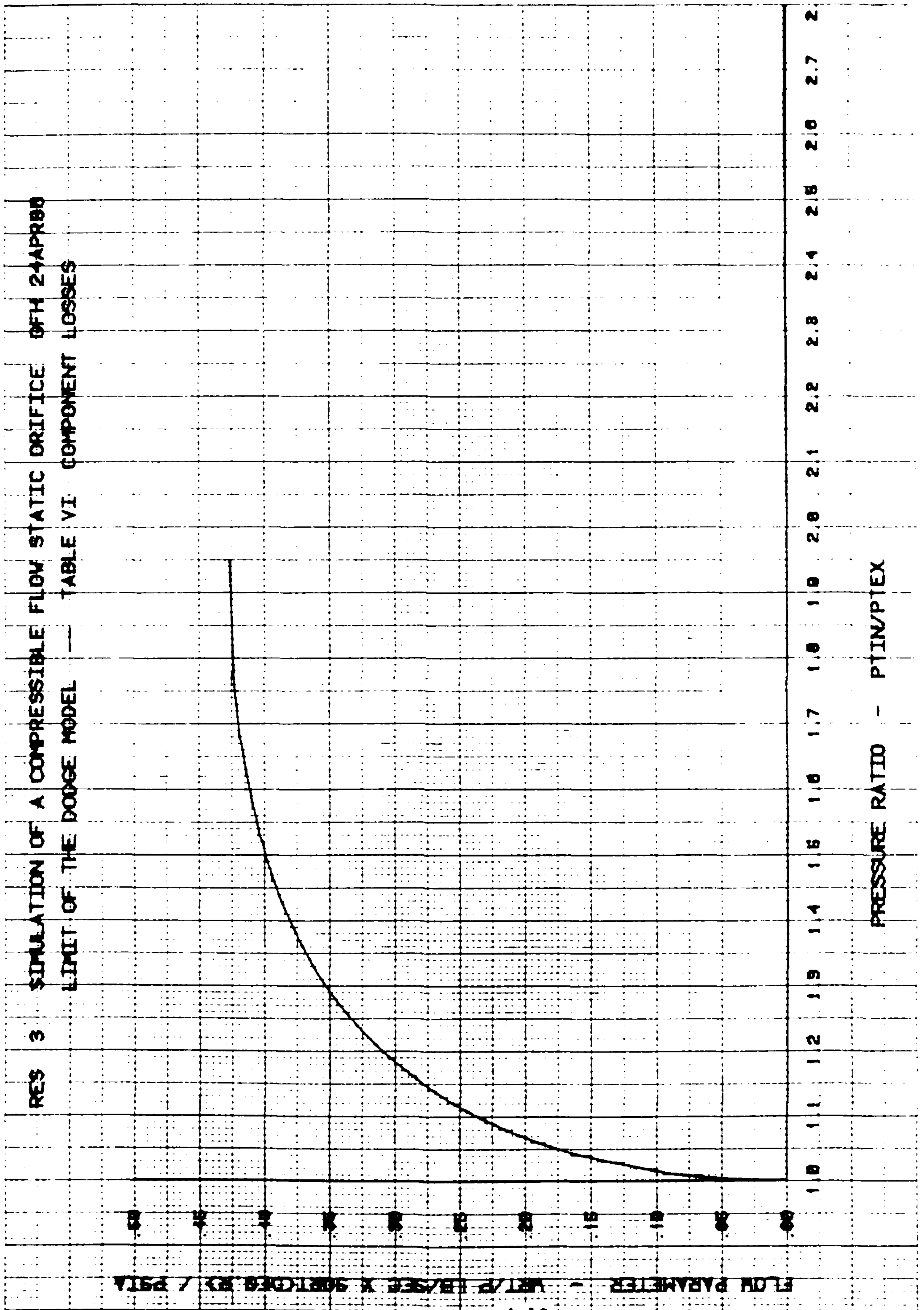
| CURVE | POINTS | AREF |
|---|---|---|
| 9 | 14 | .100000 |

RES 8(A*)COMPLEX RESTRICTION MODEL INCLUDING GENERALIZED ORIFICE RES 2

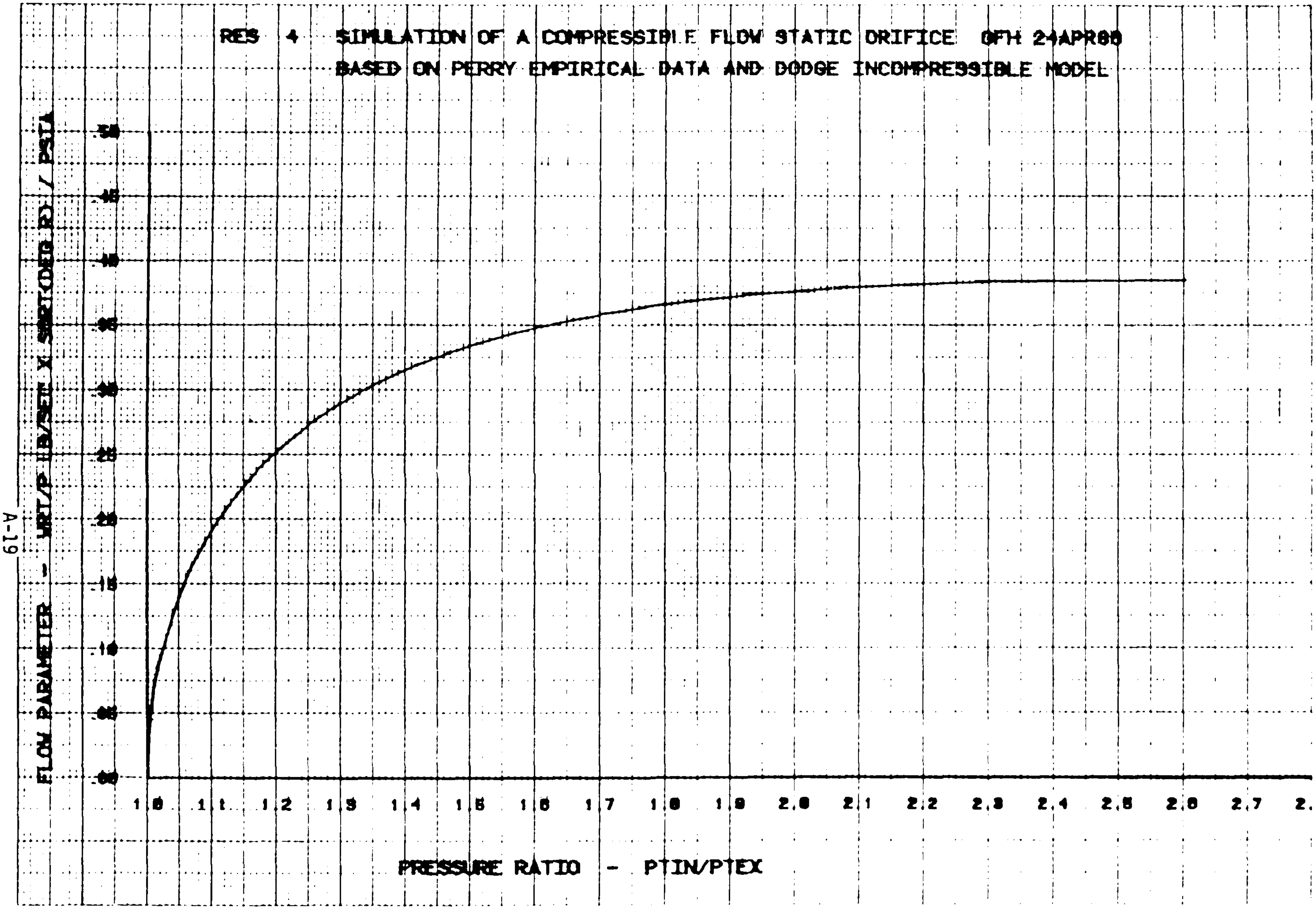
| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PR | 1.00000 | 1.00314 | 1.01523 | 1.03525 | 1.06251 | 1.09627 | 1.13592 | 1.18113 | 1.23030 | 1.28164 | 1.33300 | 1.38218 | 1.42377 | 1.43941 |
| PHI | 0.0 | 0.04294 | 0.09370 | 0.14054 | 0.18349 | 0.22253 | 0.25766 | 0.28889 | 0.31622 | 0.33965 | 0.35917 | 0.37478 | 0.38649 | 0.39040 |

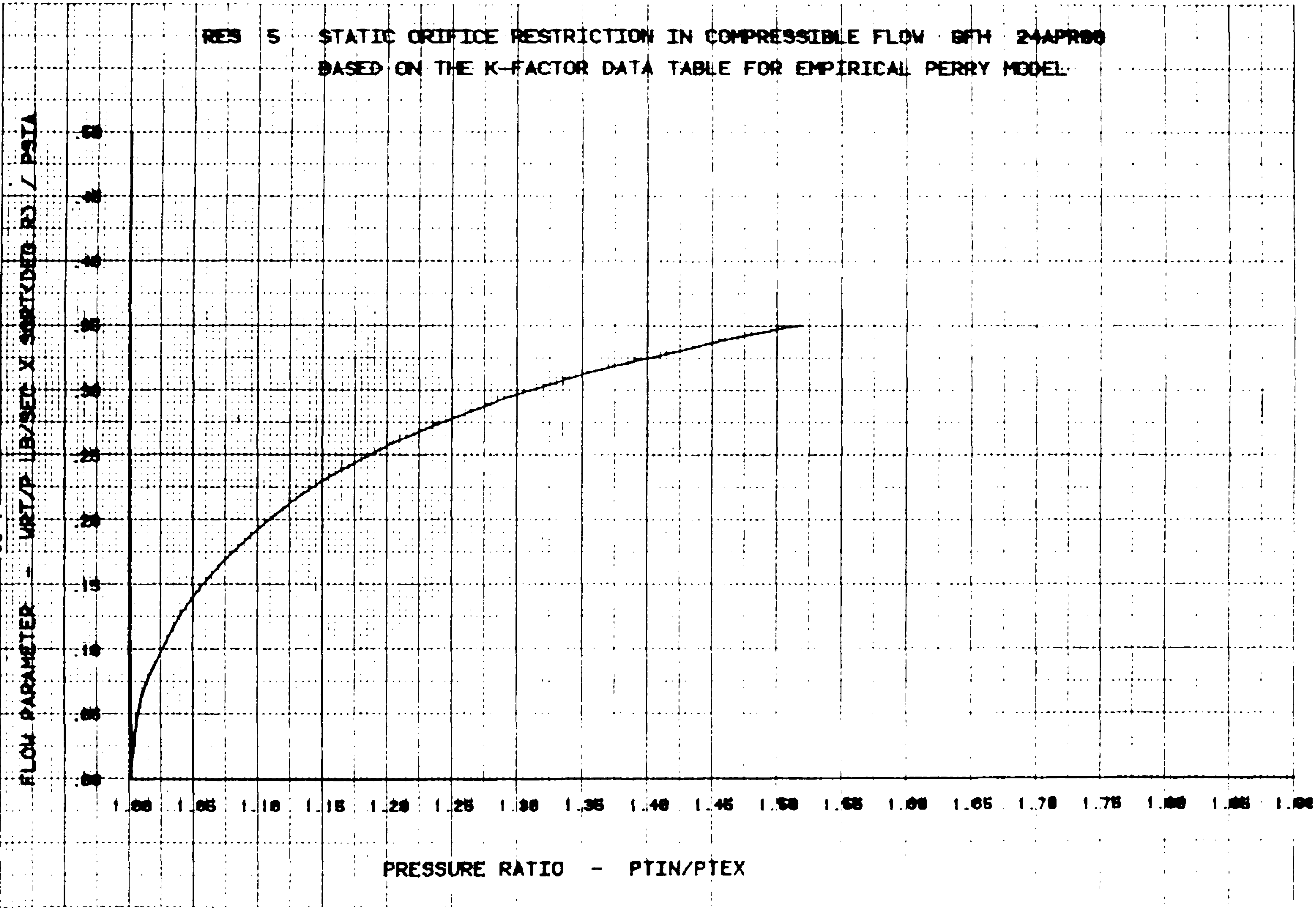

RES 1 SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW 24APR88
BASED ON THE DODGE MODEL - L/D = 1.2, LEADING EDGE RADIUS
FLOW PARAMETER - WBT/P LB/SEC X SQRT(DEG R) / PSIA
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
1.00
1.05
1.10
1.15
1.20
1.25
1.30
1.35
1.40
1.45
1.50
1.55
1.60
1.65
1.70
1.75
1.80
1.85
1.90
PRESSURE RATIO - PTIN/PTEX

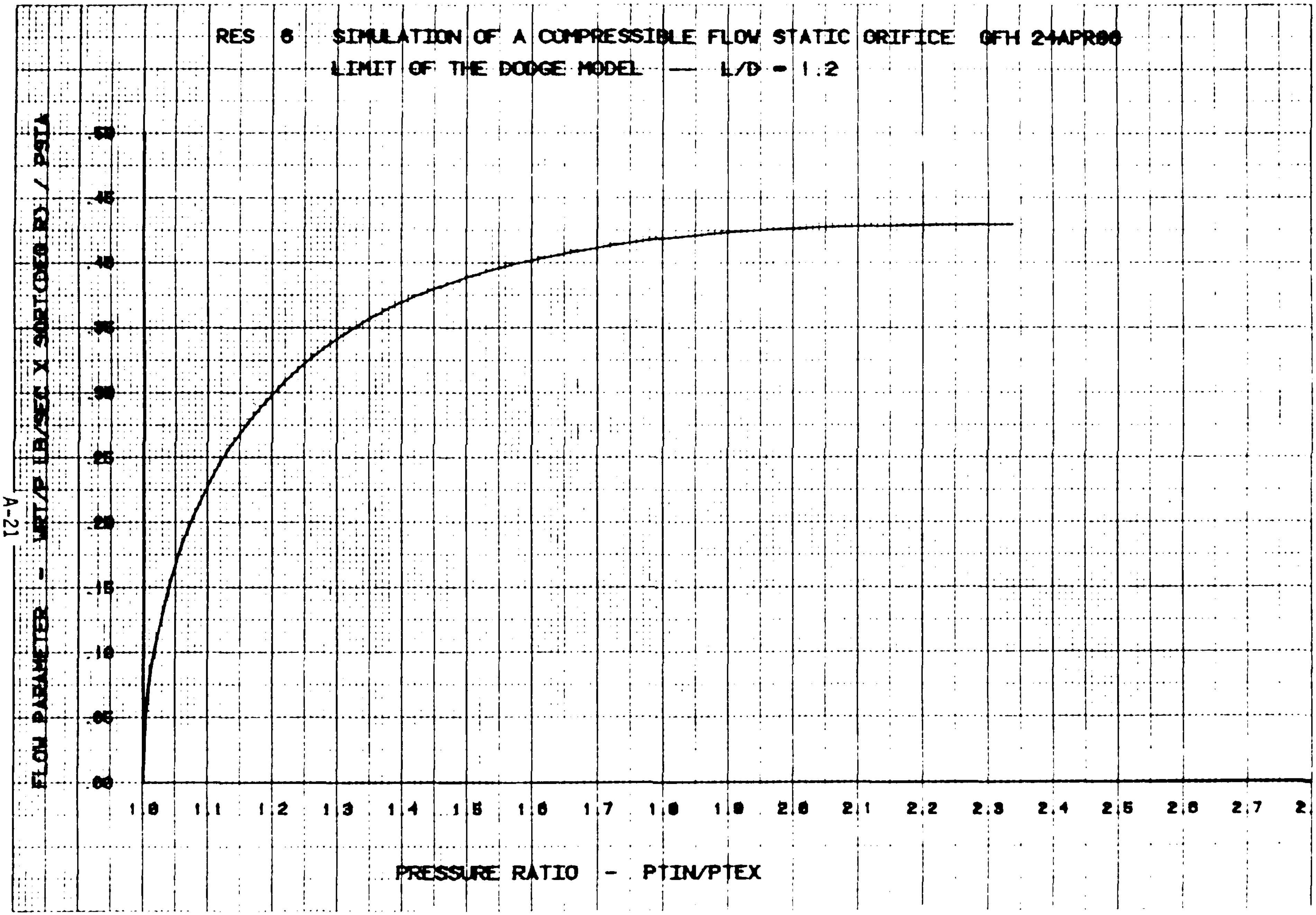

RES 2 SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW 24APR80
BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE
FLOW PARAMETER - WRT/P LB/SEC X SQRT(DEG R) / PSIA
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
.00
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
PRESSURE RATIO - PTIN/PTEX

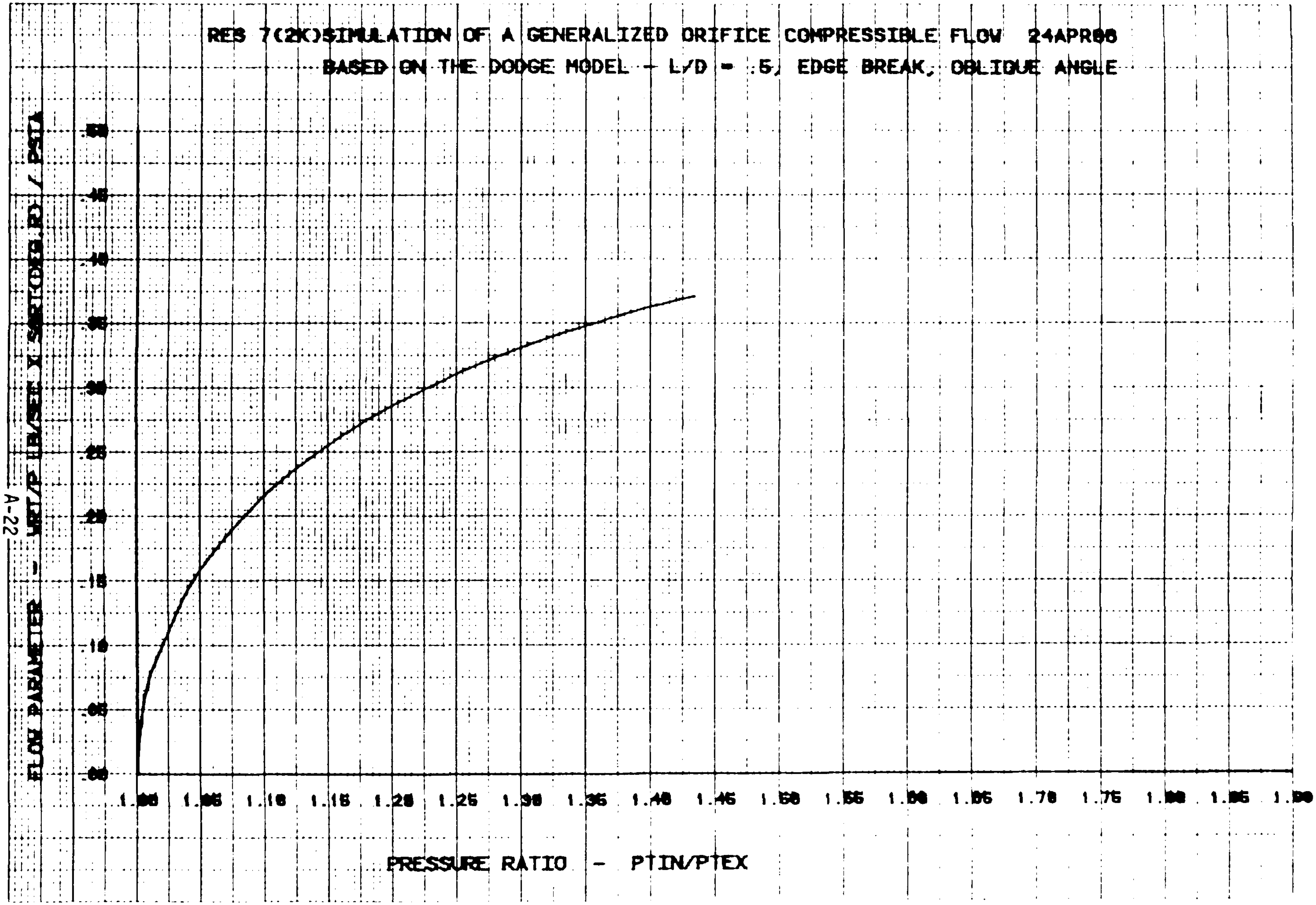


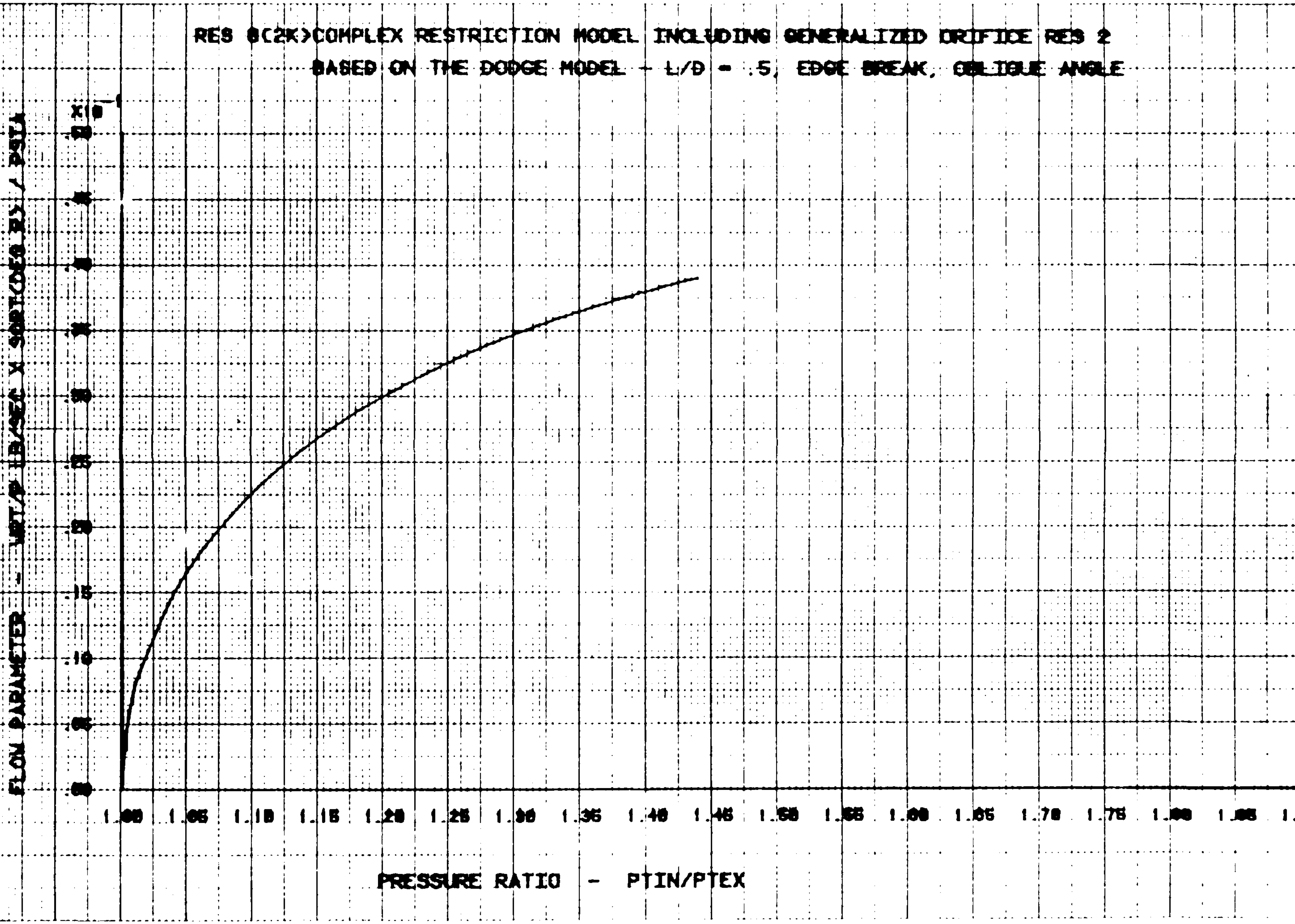
RES 3 SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE DFH 24APR88
LIMIT OF THE DODGE MODEL — TABLE VI COMPONENT LOSSES
PRESSURE RATIO - PTIN/PTEX
1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8
FLOW PARAMETER

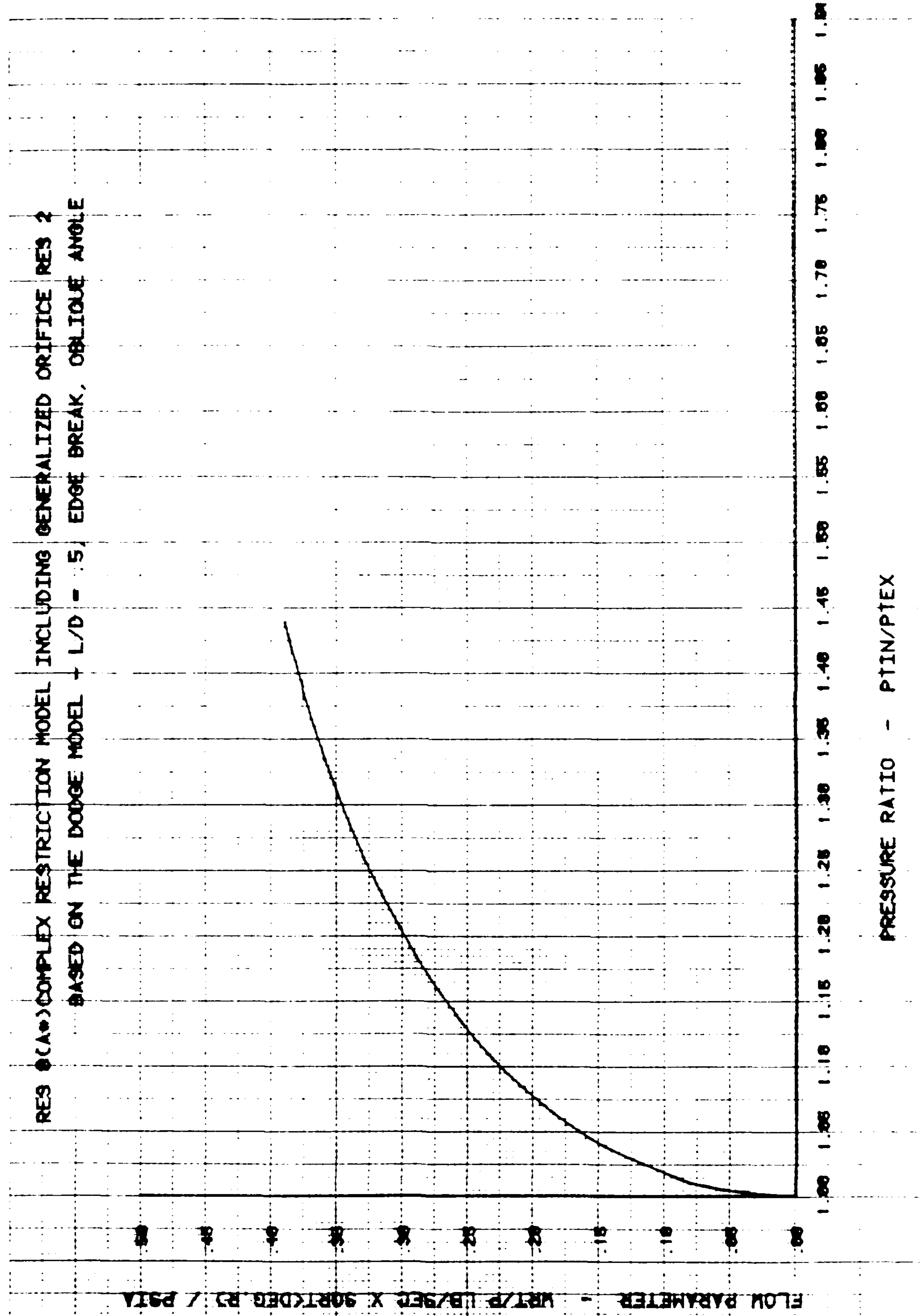

RES 4 SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE GFH 24APR80
BASED ON PERRY EMPIRICAL DATA AND DODGE INCOMPRESSIBLE MODEL
FLOW PARAMETER - WRT/P LB/SEC X SQRT(DEG R) / PSIA
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
.00
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
PRESSURE RATIO - PTIN/PTEX


RES 5 STATIC ORIFICE RESTRICTION IN COMPRESSIBLE FLOW GFH 24APR80
BASED ON THE K-FACTOR DATA TABLE FOR EMPIRICAL PERRY MODEL
FLOW PARAMETER - WRT/P LB/SEC X SQRT(DEG R) / PSIA
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
1.00
1.05
1.10
1.15
1.20
1.25
1.30
1.35
1.40
1.45
1.50
1.55
1.60
1.65
1.70
1.75
1.80
1.85
1.90
PRESSURE RATIO - PTIN/PTEX


RES 6 SIMULATION OF A COMPRESSIBLE FLOW STATIC ORIFICE GFH 24APR80
LIMIT OF THE DODGE MODEL — L/D = 1.2
FLOW PARAMETER - WRT/P LB/SEC X SQRT(DEG R) / PSIA
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
.00
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
PRESSURE RATIO - PTIN/PTEX


RES 7(2K)SIMULATION OF A GENERALIZED ORIFICE COMPRESSIBLE FLOW 24APR86
BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE
PRESSURE RATIO - PTIN/PTEX
1.25
1.45
1.70
1.75


RES 8(2K)COMPLEX RESTRICTION MODEL INCLUDING GENERALIZED ORIFICE RES 2
BASED ON THE DODGE MODEL - L/D = .5, EDGE BREAK, OBLIQUE ANGLE
FLOW PARAMETER - WRT/P LB/SEC X SQRT(DEG R) / PSIA
.15
.10
1.05
1.10
1.15
1.20
1.25
1.30
1.35
1.40
1.45
1.50
1.55
1.60
1.65
1.70
1.75
PRESSURE RATIO - PTIN/PTEX



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